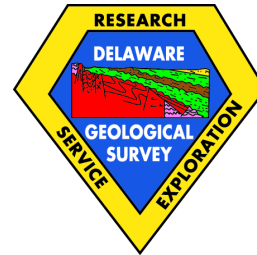


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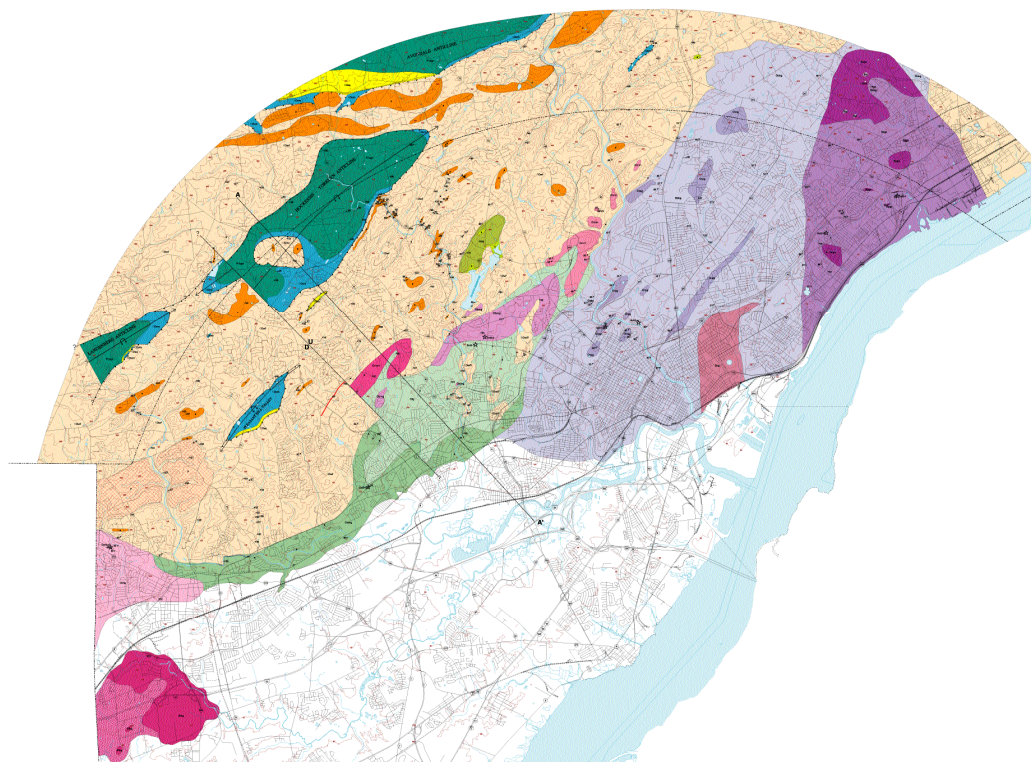


REPORT OF INVESTIGATIONS NO. 59

BEDROCK GEOLOGY OF THE PIEDMONT OF DELAWARE AND ADJACENT PENNSYLVANIA

by

Margaret O. Plank¹, William S. Schenck¹, LeeAnn Srogi²

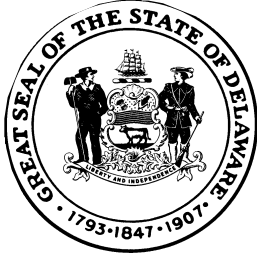


University of Delaware
Newark, Delaware

2000

¹Delaware Geological Survey

²West Chester University



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BEDROCK GEOLOGY OF THE PIEDMONT OF DELAWARE AND ADJACENT PENNSYLVANIA

Margaret O. Plank, William S. Schenck, and LeeAnn Srogi

ABSTRACT

This report accompanies a new map that revises the original bedrock geologic maps of the Delaware Piedmont compiled by Woodruff and Thompson and published by the Delaware Geological Survey (DGS) in 1972 and 1975. Combined detailed mapping, petrography, geochemistry, and U-Pb geochronology have allowed us to redefine two rock units and formally recognize eleven new units. A section of the Pennsylvania Piedmont is included on the new map to show the entire extent of the Mill Creek Nappe and the Arden Plutonic Supersuite.

The Appalachian Piedmont province of Delaware and adjacent Pennsylvania records the collision of a magmatic arc with a continental landmass and adjacent forearc basin sediments during the early Paleozoic. As a result of this collision, the rocks are intensely deformed and metamorphosed to the amphibolite and granulite facies. The oldest rocks are Grenville-age layered gneiss, migmatite, and amphibolite that are correlated with the Baltimore Gneiss, Maryland. The Grenville-age rocks are unconformably overlain by the Late Proterozoic to early Paleozoic Setters Formation and the Cockeysville Marble of the Glenarm Group. These three rock units are exposed in the Mill Creek Nappe.

The Wissahickon Formation is a thick sequence of sediments deposited in a forearc basin that are now metamorphosed and in thrust contact with the rocks of the Mill Creek Nappe. Much of the Wissahickon Formation shows repetition of layers characteristic of distal turbidites. Included within the metamorphosed sediments are an ultramafic-mafic lens, a thin diabase dike, and two types of amphibolites: Type 1, (the Kennett Square amphibolite) with trace element chemistry characteristic of basalts formed at a spreading center (i.e., N-MORBS and E-MORBS) and type 2, (the White Clay Creek amphibolite) with trace element chemistry characteristic of intraplate basalts.

The Wilmington Complex, originally defined and mapped by Ward (1959), has been redefined and based on trace element chemistry is part of an early Paleozoic magmatic arc. The arc is composed of three felsic metaplutons named the Brandywine Blue Gneiss (locally called "blue rocks"), the Barley Mill Gneiss, and the Christianstead Gneiss; two gabbroic, metaplutons, the Montchanin Metagabbro and the Mill Creek Metagabbro; three metavolcanic units, Rockford Park Gneiss, the Windy Hills Gneiss and the Faulkland Gneiss; and three undeformed plutons, the Arden Plutonic Supersuite, the Bringhurst Gabbro and the Iron Hill Gabbro.

Uranium-lead (U-Pb) dates on zircons of Wilmington Complex samples were obtained through the cooperation of John N. Aleinikoff, U. S. Geological Survey. Igneous zircons in a felsic gneiss in the Brandywine Blue Gneiss are dated at 476 ± 6 Ma and in the Rockford Park Gneiss at 476 ± 4 Ma. Metamorphic zircons in the Brandywine Blue Gneiss are dated at 432 ± 6 Ma. Similar U-Pb dates on igneous zircons are reported for felsic gneisses in the Barley Mill Gneiss, 470 ± 9 Ma, the Christianstead Gneiss, 488 ± 8 Ma, the Faulkland Gneiss, 482 ± 4 Ma, and the Windy Hills Gneiss, 481 ± 4 Ma. The U-Pb date reported for igneous zircons in the undeformed Arden Plutonic Supersuite are younger, 434 ± 4 Ma. Trace element chemistry on a mafic sample from the Arden indicates the rock was an E-MORB probably formed during late extension within the arc at about 434 Ma.

Metamorphic field gradients in the Glenarm Group, Wissahickon Formation, Faulkland Gneiss, and Windy Hills Gneiss increase toward the granulite facies of the Brandywine Blue Gneiss and the Rockford Park Gneiss in Delaware. Thus, the 432 ± 6 Ma age on the metamorphic zircons in the Brandywine Blue Gneiss probably date this granulite facies metamorphic event. The undeformed plutons probably intruded the older rocks of the Wilmington Complex during the metamorphic event and were possibly a result of the high heat flow that accompanied this event.

The James Run Formation in the type locality near Baltimore, Maryland is dated at 450 to 465 Ma (Horton et al, 1998). This is significantly younger than the 470 to 488 Ma ages reported for the Wilmington Complex. Thus, we have separated the James Run Formation from the Wilmington Complex and suggest the Cecil County volcanic complex assigned to the James Run Formation by Higgins in 1972 may be equivalent to the Wilmington Complex.

INTRODUCTION

This report accompanies the new map of the bedrock geology of the Delaware and southeastern Pennsylvania Piedmont (Plate 1) by Schenck et al., (2000). It describes the geology of the Piedmont as observed by the authors during several years of mapping and ongoing research. The map covers all or portions of these U. S. Geological Survey 7.5-minute quadrangles: West Grove, Kennett Square, Wilmington North, Marcus Hook, Newark West, Newark East, and Wilmington South. A portion of the Pennsylvania Piedmont is included in the map in order to show the extent of the Mill Creek Nappe and the Arden Plutonic Supersuite. The southern boundary of the Piedmont bedrock is the updip limit of the Potomac Formation (Woodruff and Thompson, 1972, 1975). Soil, regolith, and surficial deposits of Quaternary age are not shown.

Our map revises the original bedrock geologic maps of Delaware compiled by Woodruff and Thompson (1972, 1975). Since publication of those maps, the Baltimore Gneiss (Higgins et al. 1973) and the Setters Formation (Woodruff and Plank, 1995) have been identified for the first time in Delaware. In addition eleven new units are defined, named, and mapped. A diabase dike and ultramafic lens have been identified and mapped.

Purpose and Scope

The update of earlier work and mapping of new units is important not only to geologists, but also to hydrologists who wish to understand the distribution of water resources, to engineers who need bedrock information during construction of roads and buildings, to government officials and

agencies who are planning for residential and commercial growth, and to citizens who are curious about the bedrock under their homes. Each rock unit on our new map is described in this report, and although the information is detailed and technical, we have attempted to make it broad enough to provide information at all levels of interest.

Formal names are assigned to all rock units according to the guidelines of the 1983 North American Stratigraphic Code (NACSN, 1983) herein referenced as the 1983 Code. With the exception of the Baltimore Gneiss and the Setters Formation, the new units occur within the redefined Wilmington Complex and are classified as lithodemes. Lithodemic stratigraphy allows us to map individual rock units within the Wilmington Complex without a complete understanding of the complex relationships that exist between them.

Wilmington and its suburbs are undergoing intensive development, and outcrops are sparse, commonly limited to stream valleys, old quarries, and construction sites. Much of our work was focused on visiting both old and temporary exposures, describing the rocks, and documenting the information. We have gathered structural and lithologic data on more than 900 rock exposures. Some of these outcrops are identified by a DGS identification number (e.g. Bb25-c) throughout this report. All data for outcrops used for this study are accessible through the DGS Data Repository¹. Type and reference section maps with outcrop explanations for each rock unit are included in the Appendix. Sample locations for U-Pb age analysis are plotted on Plate 1. Results of the petrographic analyses of thin sections are available in the files of the DGS.

Geochemical analyses of the mafic rocks provided a breakthrough in our efforts to subdivide units within the Wilmington Complex. We found that samples could be grouped by their trace element concentrations and the groups identified spatially in the field. A detailed report on the geochemistry of these rocks will be published by Plank et al. (in press) as DGS Report of Investigations No. 60.

In areas where original relationships have been obscured by polyphase deformation, geochronology is useful in understanding stratigraphy and petrogenetic processes. John N. Aleinikoff, U. S. Geological Survey, provided U-Pb analyses of 7 Wilmington Complex samples. We have included these dates in our rock descriptions and have used them to organize the rock units in the correlation chart in Plate 1.

Margaret O. Plank was responsible for the geochemistry and much of the technical writing of the rock unit descriptions. LeeAnn Srogi wrote the description of the Arden Plutonic Supersuite, and William S. Schenck was responsible for the production of the map and the assembly of all the information into this report.

Regional Geologic Setting

The study area is located within the Appalachian Piedmont Province and includes the Piedmont of Delaware and adjacent Pennsylvania. The Delaware Piedmont covers roughly 82 square miles and consists mainly of metasedimentary, metaigneous, and igneous rocks that were involved in a collision between an early Paleozoic magmatic arc and a continental margin. Most of the rocks are highly deformed and

metamorphosed with metamorphic grade ranging from amphibolite to granulite facies (Thompson, 1979; Crawford and Crawford, 1980; Thompson, 1981; Plank and Schenck, 1997).

The Delaware Piedmont can be divided into two major belts of contrasting lithologies that trend northeast-southwest. One belt, located in the eastern map area, consists mainly of metasedimentary, metaigneous, and igneous rocks of the Wilmington Complex. These rocks represent the exhumed roots of an early Paleozoic magmatic arc with its associated volcanic rocks and related plutons. This belt forms the bedrock east of Route 202 and under the city of Wilmington.

The second belt contains the Precambrian basement rocks known as Baltimore Gneiss, the Paleozoic metasedimentary cover rocks of the Glenarm Group (Setters and Cockeysville formations), and the Wissahickon Formation. These rocks, located in the western map area, were once part of an ancient continent or more likely a microcontinent (Faill, 1997), nearshore sediments, and marine sediments deposited in a forearc basin.

Acknowledgments

The authors express appreciation and thanks to the many landowners and developers who allowed use of their property for field mapping. We have walked over most of the Delaware Piedmont, knocked on many doors, and found the residents unfailingly helpful and interested in our project.

We thank the Pennsylvania Geological Survey for permission to publish adjacent areas in Pennsylvania on Plate 1 in order to show the complete map pattern of the Mill Creek Nappe and the Arden Plutonic Supersuite.

We are indebted to other Appalachian geologists, Howell Bosbyshell, Mary Emma Wagner, and Jonathan Kim who shared their ideas and knowledge, and to Thomas R. Armstrong and John N. Aleinikoff of the U. S. Geological Survey for their help with geochronology, and advice. We also thank Richard N. Benson, James E. Alcock, Thomas R. Armstrong, John N. Aleinikoff, Maria Louisa Crawford, Rodger T. Faill and Robert C. Smith for constructive reviews of the manuscript.

The geochemical data were supplied by Terry A. Plank, then of the University of Kansas and now Boston University, and enhanced by additional data from Robert C. Smith and John H. Barnes of the Pennsylvania Geological Survey.

And finally, thank you to Nicole M. Minni for the digitizing and creation of the digital version of the enclosed geologic map.

GEOLOGIC UNITS

Baltimore Gneiss

Definition. The name Baltimore Gneiss has been applied to the basement gneisses that occupy the lowest stratigraphic level observed in the central Piedmont. The gneisses are exposed in the cores of 13 domes, anticlines, or nappes that extend from Baltimore, Maryland, to Philadelphia, Pennsylvania. In the map area, the Baltimore Gneiss is exposed in the Mill Creek Nappe (Figure 1) and the Avondale anticline located in the West Grove, Kennett Square, and Newark East quadrangles.

¹ Outcrop location, lithology, and strike and dip information in the form of an Excel spreadsheet are accessible through the DGS Data Repository located under "Publications" on the DGS web page at <http://www.udel.edu/dgs>.

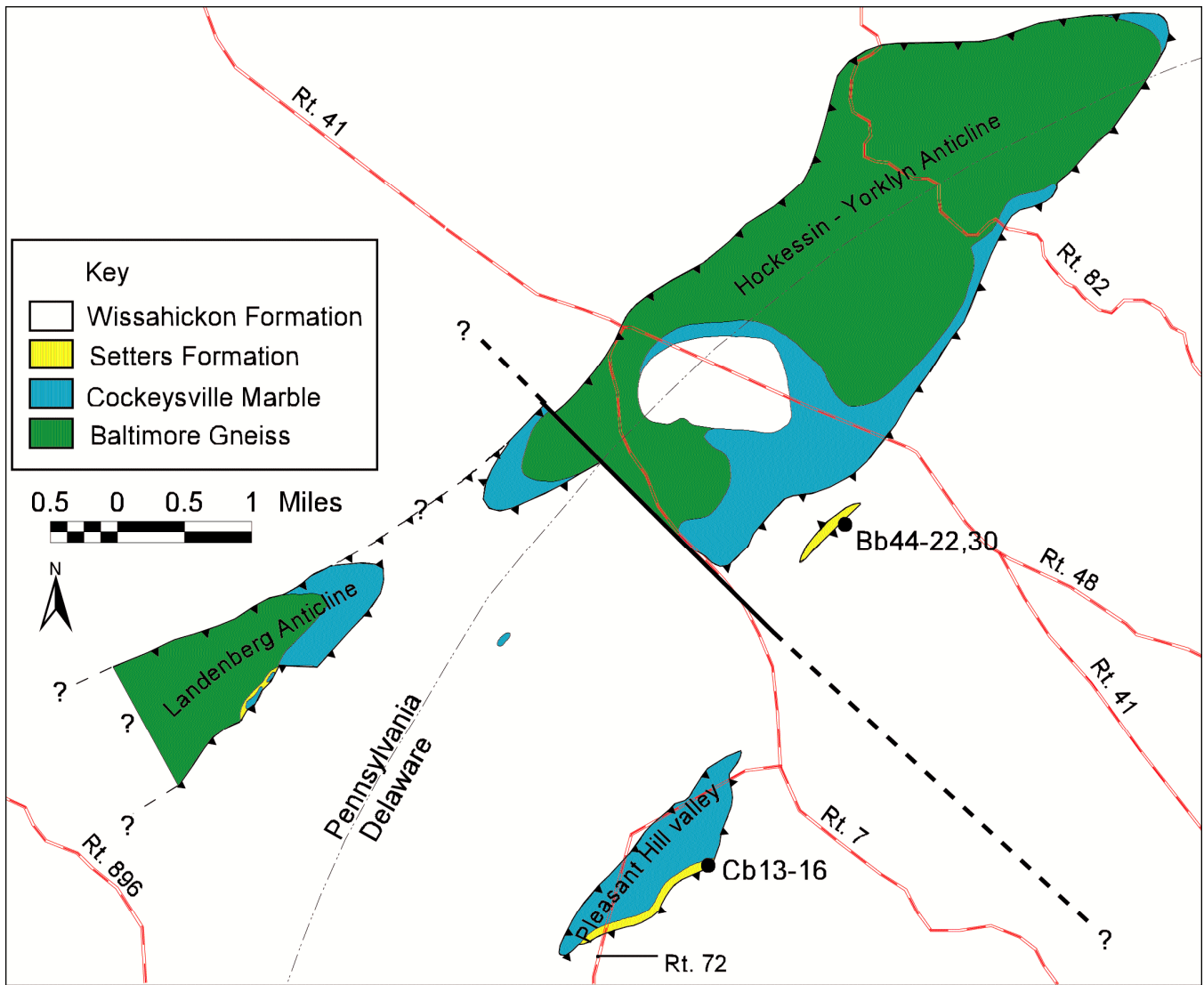


Figure 1. Map of the Mill Creek Nappe showing the location of the Landenberg and Hockessin-Yorklyn anticlines and Pleasant Hill valley

Historical Background. Williams (1892) first described the Baltimore Gneiss as the well-stratified gneisses that lie below the Coastal Plain sediments along Jones Falls and Gwynns Falls in Baltimore, Maryland. These sites were considered the type locality for the Baltimore Gneiss, and subsequent work applied the name Baltimore Gneiss to all the basement gneisses that lie in the cores of dome-like structures in the central Piedmont (Matthews 1904; Bascom et al., 1909; Knopf and Jonas, 1923). In the 1960s, Hopson (1964), and Southwick (1969) showed that the layered gneisses at Jones and Gwynns Falls are texturally and chemically different from the Baltimore Gneiss in the domes surrounding Baltimore and correlated them with the younger James Run Gneiss. Later work by Tilton et al. (1970) confirmed the younger age for these layered gneisses. Crowley (1976) redefined the Baltimore Gneiss in the domes surrounding Baltimore, described type sections for four members, and named a new unit, the Slaughterhouse Gneiss.

Baltimore Gneiss was not identified in Delaware until Higgins et al. (1973) recognized a deep magnetic low on the aeromagnetic map of Henderson et al. (1963) and verified

the presence of a dome cored by basement gneisses along the Pennsylvania-Delaware line. After a brief reconnaissance survey, they named this body the “Mill Creek Dome.” Recently, the Mill Creek Dome has been mapped in detail, modeled as a thrust nappe, and renamed the Mill Creek Nappe (Alcock, 1991; Woodruff and Plank, 1995; Alcock and Wagner, 1995; Schenck and Plank, 1995; Plank and Schenck, 1997).

Although the Baltimore Gneiss of the Mill Creek Nappe bears a Grenville-age metamorphism and was probably part of the Grenville orogen, it is lithically different from the Grenville rocks of the Laurentian margin (Faill, 1997). It is possibly a remnant of a microcontinent that originated elsewhere, possibly Baltica or South America (Drake et al., 1988; Faill and Wiswall, 1994; Faill, 1997).

Boundaries. The Hockessin-Yorklyn and the Landenberg anticlines, cored by Baltimore Gneiss, and the Pleasant Hill valley define the Mill Creek Nappe, a thrust nappe, as a major structure that trends N45°E, parallel to the regional strike (Figure 1). The northwestern boundary of the Hockessin-Yorklyn anticline, between the Baltimore Gneiss

and the Wissahickon Formation is a thrust fault bringing Baltimore Gneiss over Wissahickon Formation to the northwest (Alcock, 1994; Woodruff and Plank, 1995). The southeastern boundary between the Baltimore Gneiss and the Glenarm Group (Cockeysville Marble and Setters Formation) is an unconformity. A northwest-southeast trending, dip-slip fault lies between the Hockessin-Yorklyn anticline and the Landenberg anticline. Uplift along the fault has moved the Hockessin-Yorklyn section to higher structural levels. A thick weathered zone along the fault suggests that this fault is younger than the early Paleozoic, high temperature ductile deformation.

The northwestern boundary of the Landenberg anticline is also a thrust fault bringing Baltimore Gneiss over Wissahickon Formation to the northwest (Alcock, 1994; Plank and Schenck, 1997); however, here the stratigraphic sequence is upside down with Cockeysville Marble on the bottom and Baltimore Gneiss on top. This arrangement of the units may indicate that the Landenberg is part of the lower limb of the of the Mill Creek Nappe. Lack of outcrop has prevented identification of Baltimore Gneiss in the area southwest of the Landenberg anticline (Plate 1).

Reference Section. In accordance with the 1983 Code, the Baltimore Gneiss is currently defined in Delaware as a lithostratigraphic unit that has been correlated with the Baltimore Gneiss in Maryland and Pennsylvania (Pickett, 1976; Thompson, 1979; Woodruff and Plank, 1995). The outcrop that occurs west of Yorklyn and south of the Red Clay Creek flood plain has been selected as the Delaware reference section (Bb25-b).

Lithology. Three lithologies have been identified within the Baltimore Gneiss in the Mill Creek Nappe: granitic gneiss, hornblende-biotite gneiss, and amphibolite with or without pyroxene. Lack of exposure prevents these lithologies from being mapped separately. Granitic gneisses with swirling leucosomes and irregular, biotite-rich, restite layers constitute approximately 75 to 80 percent of the exposed rocks. Pegmatites are commonly associated with the granitic gneisses and are exposed in a series of abandoned quarries along the northwestern boundary of the Hockessin-Yorklyn anticline (Woodruff and Plank, 1995). Several of the thicker pyroxene-bearing amphibolites resemble the diabase dikes that intrude the West Chester prong and Avondale anticline (Wagner and Crawford, 1975; Mary Emma Wagner, 1988, personal communication).

Petrography. The granitic gneiss is composed of quartz, plagioclase, biotite, and microcline. Minor and accessory minerals are garnet, muscovite, magnetite, ilmenite, sphene, apatite, and zircon (Woodruff and Plank, 1995). The plagioclase is chiefly oligoclase with myrmekite concentrated along grain boundaries. Much of the granitic gneiss is migmatitic.

The hornblende gneiss contains plagioclase, quartz, hornblende, and biotite with/without orthopyroxene. Accessory minerals are garnet, muscovite, clinozoisite, perthitic orthoclase, iron-titanium oxides, sphene, and apatite. Hornblende grains are pleochroic in shades of brown-green and green.

The amphibolites are composed of subequal amounts of hornblende and plagioclase with minor quartz, biotite, clinopyroxene, and orthopyroxene (Woodruff and Plank,

1995). Locally the hornblende grains are color zoned with a brown-green core and a blue-green rim. The change from core to rim suggests either changing metamorphic conditions during crystallization of the rim, or a second metamorphic event.

Microtextures in most lithologies indicate syntectonic recrystallization. Feldspar grains are partially twinned, quartz grains are recrystallized to subgrains of various sizes with undulatory extinction, and mica flakes are commonly sheared into stringers of small grains.

Metamorphism. In the Baltimore, Maryland, area, the Baltimore Gneiss records two periods of metamorphism, one during the mid-Proterozoic, approximately 1,100 Ma, and a second during the Paleozoic, 440 to 470 Ma (Tilton et al., 1958; Hopson, 1964; Tilton et al. 1970). Crawford and Crawford (1980) describe the metamorphic history for the Delaware and Pennsylvania basement gneisses based on evidence of superposition of three metamorphic episodes: M1, a regional high grade granulite episode at 1100-980 Ma; M2, a low pressure, high temperature event; and M3, an upper amphibolite facies event. The later two are lower to mid-Paleozoic in age. Relict orthopyroxene in the hornblende gneisses of the Mill Creek Nappe preserves evidence for M1, whereas most of the Baltimore Gneiss rocks in the Mill Creek Nappe preserve only upper amphibolite facies metamorphism, M2.

Deformation. The fabric in the gneisses grades from uniform and weakly layered to strongly layered and migmatitic. The several metamorphic events and deformations experienced by these rocks obscure the genetic relationships. Hornblende gneisses and amphibolite layers vary in thickness from less than 0.25 in to tens of feet. Strikes and dips of foliations are variable, except along the southeastern boundary of the Hockessin-Yorklyn anticline and Pleasant Hill valley where foliations parallel those in the Cockeysville and Wissahickon formations.

Age. On the basis of radiogenic dating of zircon and feldspar, Tilton et al. (1958) and Tilton et al. (1970) suggest a period of recrystallization at 1,100 Ma for migmatitic rocks in the gneiss domes around Baltimore. U-Pb isotopic studies on zircons in the Baltimore Gneiss of the West Chester prong and Avondale anticline (Grauert et al. 1973) point to a metamorphic period between 980 and 1,100 Ma. Aleinikoff et al. (1997) show that volcanic layers in three of the Baltimore Gneiss domes in or around Baltimore were deposited at $1,245 \pm 5$ Ma and were affected by subsequent events at $1,210 \pm 5$, $1,177 \pm 8$, and about 1,030 Ma. U-Pb dating of metamorphic sphene indicates Paleozoic metamorphic events at about 450, 382 ± 5 , 353 ± 8 , and about 280 Ma, corresponding in general to the Taconic, Acadian, and Alleghenian orogenies, respectively. No ages have been determined for the Baltimore Gneiss in the Mill Creek Nappe in Delaware or Pennsylvania.

Setters Formation

Definition. The Setters Formation is a metasedimentary unit composed of quartzite and feldspathic quartz-mica schist and gneiss. It is the basal unit of the Glenarm Group, separated from the underlying Baltimore Gneiss by a discontinuity and conformable with the overlying Cockeysville Marble. The Setters Formation in the Mill

Creek Nappe is missing in most places between the Baltimore Gneiss and Cockeysville Marble. This is probably the result of either thinning by thrusting or nondeposition.

Along the south side of the Avondale anticline, a thick quartzite layer of the Setters Formation occurs over the Baltimore Gneiss and under the Cockeysville Formation. This quartz-rich rock, quarried and sold as "Avondale Stone," tends to split along thin micaceous partings and form flat slabs that are popular in the construction industry. Exposures of Setters are located within the Newark East, Kennett Square, and West Grove quadrangles.

Historical Background. The Setters Formation as named by Williams (1891) for Setters Ridge, Maryland, a 160-foot-high ridge of quartzite that stands prominently above a marble valley. Since it was first described, the Setters has been widely recognized in Maryland and Pennsylvania where it occurs as discontinuous horizons around the cores of domes or anticlines of Baltimore Gneiss.

The Setters was originally assigned to the stratigraphic sequence of Setters Formation, Cockeysville Marble, and Wissahickon Formation and was placed in the Glenarm Series (Knopf and Jonas, 1923). The stratigraphy of the Glenarm Series has been changed many times. Today, only the Setters Formation and Cockeysville Marble remain in what is now the Glenarm Group. The Wissahickon Formation in Delaware and southeastern Pennsylvania, now the Loch Raven and Oella formations in Maryland, are thought to overlie and be in thrust contact with the Glenarm Group (Drake, 1993; Alcock, 1994; Plank and Schenck, 1997). References and a detailed history of the Setters Formation can be found in Plank and Schenck (1997).

Boundaries. The Setters Formation occurs on the south side of the Avondale anticline where it overlies the Baltimore Gneiss and is overlain by the Cockeysville Marble and Wissahickon Formation. The Setters Formation is also found in four locations within the Mill Creek Nappe: (1) in Eastburn's Quarry, Pleasant Hill valley, where it overlies the Cockeysville Marble; (2) underlying the Cockeysville Marble at 490 ft in a well adjacent to Eastburn's Quarry (Cb13-16; Figure 1); (3) both overlying and underlying the Cockeysville Marble in a test well drilled southeast of the Hockessin-Yorklyn anticline (Bb44-22, 30; Figure 1); and (4) overlying the Cockeysville Marble on the southeast side of the Landenberg anticline (Plank and Schenck, 1997).

Reference Section. The Setters Formation is currently defined in the map area as a lithostratigraphic unit that has been correlated with the Setters Formation in Maryland. A Pennsylvania reference section is exposed in quarries on the southeast side of the Avondale anticline. Quartzite and micaceous schist are exposed along Pa. Route 138 (Old Baltimore Pike) near the intersection with Route 41 (Ba14-a) in the community of Avondale, Pennsylvania. A Delaware reference section for the Setters is an outcrop in Eastburn's Quarry (Cb12-a).

Lithology. The Setters Formation is composed of two lithologies, a micaceous, sometimes garnet-rich schist with cross cutting pegmatites, and quartz-rich psammitic gneiss. Contacts between the two lithologies are gradational.

In the quarries at Avondale, the Setters Formation is composed of interlayered quartzites and micaceous schists

that commonly contain tourmaline crystals and very large garnets (up to 2 in). In Eastburn's Quarry and in quarries along White Clay Creek valley southeast of the Landenberg anticline, the Setters Formation is a quartzite that may contain small garnets. Pelitic gneiss of the Setters Formation was identified in chips from a well drilled adjacent to Eastburn's Quarry (Cb13-16).

In this study, we have revised our identification of the rock that overlies a 60-ft layer of Cockeysville Marble in the test holes drilled south of the Hockessin-Yorklyn anticline (Bb44-22 and Bb44-30). Woodruff and Plank (1995) identified the pelitic rock lying above the marble as a migmatitic facies of the Wissahickon Formation. We now recognize that the rocks in the top 80 feet of the core from test well Bb44-30 are a microcline-rich gneiss typical of the Setters Formation. In places garnets are so abundant that the rock could be defined as a garnetite. The lithology changes gradually from pelitic to psammitic as the garnets disappear and the rock becomes more quartz rich. In the garnet-rich pelitic upper 25 ft of the core, coarse pegmatite veins approximately 0.5 to 8 in thick commonly cut across the foliation.

Petrography. The Setters Formation and the Wissahickon Formation are difficult to differentiate macroscopically, but they can easily be distinguished in thin sections by identifying feldspars. Microcline with cross hatch twinning and perthitic lamellae is the most abundant feldspar in both pelitic and psammitic facies of the Setters Formation. This distinguishes the Setters Formation from the Wissahickon in which plagioclase is the most abundant feldspar and untwined orthoclase is present in small amounts. Other minerals in the pelitic and psammitic rocks of the Setters Formation are garnet, muscovite, sillimanite, quartz, and biotite with minor plagioclase. Accessory minerals are iron-titanium oxides, zircon, sphene, and apatite. Myrmekites of quartz and feldspar cluster along grain boundaries of microcline. Heteroblastic grains of quartz are commonly recrystallized to smaller subgrains. The plagioclase shows extensive alteration to green clay, and biotite may show alteration to chlorite. Sillimanite occurs as fibrolite, acicular grains, and large prisms that lie across the foliation. Modal analyses are published in Kuhlman (1975), Woodruff and Plank (1995), and Plank and Schenck (1997). Plank and Schenck (1997) compare the Setters in Delaware and Pennsylvania with the Setters in Maryland.

Strain is obvious in thin sections as quartz shows slight to extreme undulatory extinction, microcline exhibits grain-size reduction along grain boundaries, and muscovite, biotite, and sillimanite grains are strongly aligned.

Metamorphism. The mineral assemblages indicate the metamorphic grade increases from Avondale and Broad Run, Pennsylvania, where muscovite is stable, to Hockessin and Pleasant Hill valley, Delaware, where muscovite in the presence of quartz has broken down by either dehydration or partial melting to form sillimanite and K-feldspar. The breakdown of muscovite suggests peak metamorphic temperatures between 620 and 700°C. A detailed discussion of the metamorphism can be found in Plank and Schenck (1997).

Deformation and Structural Relations. In Maryland the contact between the Baltimore Gneiss and the overlying Setters Formation and Cockeysville Formation of the

Glenarm Group is an unconformity, and the contact between the Glenarm Group and the Loch Raven Formation (formerly Wissahickon Formation) is a thrust contact (Drake, 1993). This “normal sequence” is also found on the southeast side of the Avondale anticline.

Relationships in the Mill Creek Nappe are more complicated. In the quarries along Broad Run on the southeast side of the Landenberg anticline the units occur in an inverted stratigraphic sequence with the Baltimore Gneiss lying over the Setters Formation and the Setters Formation lying over the Cockeysville Marble (J. E. Alcock, personal communication, 2000). This inverted sequence may represent the lower limb of the Mill Creek Nappe or is the result of complex folding.

In Eastburn’s Quarry, Pleasant Hill valley, Delaware, slabs of garnet-bearing psammitic gneiss of the Setters overlie the marble (Woodruff and Plank, 1995). The contact is never exposed, but the strike and dip of both units is concordant at N33°E, 23°SE. Pelitic Setters was also identified in chips from a well drilled adjacent to Eastburn’s Quarry (Cb13-16). In the well the top of the Setters lies at 490 ft, below 430 ft of marble (Plank and Schenck, 1997).

The sequence of units in the test holes drilled south of the Hockessin-Yorklyn anticline (Bb44-22 and Bb44-30, Figure 1) is different. We now recognize from thin sections and gamma logs that the Wissahickon Formation lies under a sequence of 30 ft of Setters Formation, 60 ft of Cockeysville Marble and 80 ft of Setters Formation. The identification of the Setters below the Cockeysville Marble is based on the gamma log (Woodruff and Plank, 1995). This arrangement of units on the south side of Pleasant Hill valley and the Hockessin-Yorklyn anticline may be due to complex folding.

Summary of the structural relations of the Glenarm Group to other units in the map area (listed from structurally lowest to highest).

Pennsylvania:

Avondale: Baltimore Gneiss-Setters-Cockeysville-Wissahickon

Broad Run: Cockeysville-Setters-Baltimore Gneiss-Wissahickon

Delaware:

Eastburn’s Quarry: Baltimore Gneiss-Setters-Cockeysville-Setters-Wissahickon

Hockessin Bb44-22 and 30: Wissahickon-Setters-Cockeysville-Setters-Wissahickon

Age. Wasserburg et al. (1957) determined radiogenic potassium/argon ages on micas in the Setters in Maryland that average about 330 million years, thought to be the age of metamorphism. The age of deposition of the Glenarm has been a major geological controversy for many years with the best estimate being somewhere between latest Proterozoic and Ordovician (Higgins, 1972; Drake et al., 1989). There are no ages available for the Setters Formation in Delaware or Pennsylvania.

Cockeysville Marble

Definition. The Cockeysville Marble in Delaware and Pennsylvania is a lithostratigraphic unit correlated with exposures of marble in Cockeysville, Maryland. Like the Cockeysville in Maryland, the Cockeysville in the map area

(Plate 1) is stratigraphically associated with the Baltimore Gneiss and the Setters Formation. There are no natural exposures in the map area; data are derived from quarry exposures and from drill holes. The Cockeysville Marble consists of pure, coarsely crystalline, dolomite marble with minor calcite marble and calc-schists. It is located in the Kennett Square, West Grove, and Newark East quadrangles where it underlies the Hockessin-Yorklyn valley and Pleasant Hill valley in Delaware, and the White Clay Creek valley near Broad Run and another unnamed valley toward Kennett Square in Pennsylvania. No fossils have been preserved in the marbles.

Historical Background. The Cockeysville Marble has long been recognized as an important rock unit. In the 1800s it was used as a fertilizer to improve the yield of crops in Delaware and as dimension stone in Pennsylvania. Today it is an important aquifer providing water for a rapidly growing population.

Although Delaware’s first state geologist, James C. Booth (1841), reported a number of occurrences of marble, the first geologic maps of Delaware and southeastern Pennsylvania that included marble as a mappable unit were those of Bascom and Miller (1920) and Bascom and Stose (1932). They correlated the marble with the Cockeysville Marble in Maryland. Subsequent workers have supported this correlation and it is now well established. More recent published maps that show the marble in Delaware are those by Woodruff and Thompson (1972) and Woodruff and Plank (1995).

Knopf and Jonas (1923) originally described the Cockeysville Marble as a stratigraphic unit that lies above the Setters Formation and below the Wissahickon Formation within the Glenarm Series. This stratigraphy was well established in Maryland and was carried into southeastern Pennsylvania by Knopf and Jonas (1929). Choquette (1960) studied the Cockeysville Marble in Maryland in depth and recognized six lithologies, but he did not establish any stratigraphy. Later, Crowley (1976) developed a six-fold stratigraphy using the lithologies identified by Choquette.

Higgins (1977) redefined the Glenarm Series as the Glenarm Group and included the Setters Formation, Cockeysville Marble, and Wissahickon Group of Crowley (1976). Drake (1993) redefined the Glenarm Group as the Setters Formation and the Cockeysville Marble and interpreted the contact with the overlying metasedimentary units as a thrust. This association was upheld in Pennsylvania by Alcock (1994) and Alcock and Wagner (1995) and in Delaware by Plank and Schenck (1997). They found the Setters both above and below the Cockeysville and proposed that the contact between the Glenarm Group and the Wissahickon Formation may be a thrust fault. Evidence for a thrust interpretation for the Mill Creek Nappe is described in Plank and Schenck (1997).

Boundaries. The main bodies of Cockeysville Marble in the map area underlie broad flat valleys on the southeast side of the Hockessin-Yorklyn, Landenberg, and Avondale anticlines, and in Pleasant Hill valley. The easily eroded marble is rarely exposed; however, a lack of surface exposure, scarcity of float, and low relief on the valley floors are usually taken as evidence for underlying marble. The approximate contact with the adjacent rocks is marked by a

topographic break that can be seen in the field and identified on 7.5-minute topographic maps. The thickness of the Cockeysville Marble in the map area is estimated to be between 400 and 800 ft based on outcrop and structural interpretations. Where the marble is exposed in quarries, it is weathered, sometime to depths of more than 150 ft.

Cockeysville Marble does not occur on the northwest side of the Hockessin-Yorklyn or the Landenberg anticlines. The absence is probably due to thinning on the thrust limb or to nondeposition (Hopson, 1964; Woodruff and Plank, 1995).

Reference Section. The Cockeysville Marble is currently defined as a lithostratigraphic unit correlated with the Cockeysville Marble in Maryland. The Delaware reference section is in Eastburns Quarry (Cb12-a) south of the intersection of Rt. 72 and Upper Pike Creek Road in Pleasant Hill valley.

Lithologies. No internal stratigraphy has been recognized in the Cockeysville in Delaware or Pennsylvania; however, three lithologies, dolomite marble, calcite marble, and calc-schist, have been identified in well cores and quarries (Woodruff and Plank, 1995; Alcock, 1989).

Dolomite marble is the dominant lithology and makes up about 90 percent of the Cockeysville in the Mill Creek Nappe. It occurs as a pure, coarsely crystalline, blue-white marble that locally contains streaks or thin bands of calc-silicate minerals. Calcite marble is present in thin irregular layers within the dolomite marble. Layers of phlogopite usually define the contacts between the rock types. Calc-schist is a fine- to medium-grained, light gray rock that is phlogopite-rich and strongly foliated. Gamma-logs from wells drilled into the Cockeysville indicate that the calc-schist is most common in the upper 250 ft of the formation (Woodruff and Plank, 1995).

An interesting feature of the marble is its association with large deposits of pure white kaolin. During the 1800s, kaolin was mined from pits in the Hockessin and Pleasant Hill valleys for use in the manufacture of fine china. The kaolin appears to have formed by weathering of pegmatites. The pegmatites have no surface expression, thus they are difficult to locate except by drilling.

Petrography. Dolomite marble consists of 94 to 100 percent dolomite with calcite, phlogopite, and graphite as minor phases. Calcite marble consists of 80 to 90 percent calcite and dolomite with phlogopite, diopside, olivine and graphite as minor phases. The marbles are thoroughly recrystallized, and, in general, the mineral assemblages appear to be in equilibrium except where tremolite and talc have replaced diopside and serpentine is as pseudomorph after olivine.

The calc-schists consist of calcite and more than 50 percent silicate minerals, mainly phlogopite, microcline, diopside, tremolite, quartz, plagioclase, scapolite, and clinozoisite. Dolomite is generally absent. The variety of phases and their distribution within the calc-schists probably reflect the varying amounts of clay in the parent sediments plus some metasomatism. Choquette (1960) and Alcock (1989) suggested that metamorphic fluids channeled through silica-rich zones in dolomitic marbles were partly responsible for the generation of the silicate minerals. Modes and description of the lithologies are reported in Woodruff and Plank (1995).

Metamorphism. The mineral phases in the Cockeysville show assemblages typical of marbles metamorphosed at medium to high temperatures and medium pressures of 4 to 5 kilobars (Alcock, 1989; Woodruff and Plank 1995). A detailed study of the metamorphic assemblages in the marble on the southeast side of the Landenberg anticline can be found in Alcock (1989, 1991, and 1994). He cited peak temperatures in the marble of 575°C as evidence for a metamorphic discontinuity between the marble and the overlying Wissahickon Formation that records temperatures of 700°C south of the Landenberg anticline. Plank and Schenck (1997) found that the metamorphic thermal gradient increased to the southeast in the Hockessin-Yorklyn and Pleasant Hill valleys where assemblages in the marbles indicate temperatures >620°C.

Deformation. In general, the calc-schists possess a marked foliation expressed as compositional layering, and the dolomite marbles are massive. Folds in the calc-schists are isoclinal and recumbent to the northwest. Foliations trend N45°E, parallel to the regional strike, and dip to the southeast at a shallow angle, about 30° to 45°. For a detailed description of the deformation in the marble see Alcock (1989, 1991).

Age. Wasserburg et al. (1957) determined potassium/argon (K-Ar) ages of micas in the Cockeysville in Maryland that average about 330 million years, thought to be the age of metamorphism. As stated previously, the age of the deposition of the Glenarm has been a major geological controversy for many years. Higgins (1972) and Drake et al. (1989) estimate the age of deposition to be somewhere between latest Proterozoic and Ordovician. There are no radiometric dates available for the Cockeysville Marble in Delaware or Pennsylvania.

Wissahickon Formation

Definition. The Wissahickon Formation is an extensive sequence of pelitic and psammitic gneisses interlayered with amphibolites. With the exception of the large amphibolite bodies mapped by Bascom and Stose (1932) south of the Avondale anticline, most amphibolite layers are less than 30 ft thick. The rocks have been metamorphosed to upper amphibolite facies and isoclinally folded. The formation is located within the Wilmington North, Kennett Square, West Grove, Newark West, and Newark East quadrangles.

Historical Background. Florence Bascom (1902) named the Wissahickon Schist for the belt of mica-schist and gneiss that extends from near Philadelphia, Pennsylvania, southwestward into Cecil County, Maryland. Mathews (1905) extended the Wissahickon into the Baltimore area in Maryland and referred to it as the Wissahickon Formation. Bascom (1905) expanded the Wissahickon to include the mica schists flanking Mine Ridge and the Honeybrook Upland in southeast Pennsylvania. Thus, by 1905, nearly all the pelitic gneisses, schists, and phyllites in the central Piedmont were lumped into the Wissahickon Formation. Since that time, the Wissahickon Formation has been extensively studied and the stratigraphic nomenclature continuously revised. Today, the name Wissahickon is no longer used for rocks in central Maryland or around Mine Ridge in Pennsylvania. For a detailed summary of the history of the Wissahickon Formation in Maryland and Delaware see Schenck (1997).

Studies of the Wissahickon Formation in the Philadelphia area include those of Bascom (1905), Weiss (1949), Wyckoff (1952), Amenta (1974), Crawford and Crawford (1980), Crawford and Mark (1982), Calem (1987), Wagner and Srogi (1987), Srogi (1991), Srogi et al. (1993), and Bosbyshell et al. (1999). Wiess (1949) and Wyckoff (1952) studied the mineralogy, petrology and metamorphic facies in the Philadelphia area and found the distribution of assemblages defines a metamorphic field gradient characterized by an increase in temperature from east to west with highest temperatures recorded by rocks in the southwestern end of the schist belt. Amenta (1974) reported that the structures and microtextures in the Wissahickon Formation reveal a complex history involving five structural events and two episodes of metamorphism, M1 and M2.

Crawford and Crawford (1980) also define two metamorphic episodes in the Wissahickon Formation, but designate them as M2 and M3. M1 is the 1,100- to 980 Ma regional high grade episode that affects only the Baltimore Gneiss basement rocks. M2 is an early Paleozoic (ca. 441 Ma) high-temperature granulite event that is centered in the Wilmington Complex (Grauert and Wagner, 1975). M3 is a high pressure, lower temperature event that overprints the area. Its timing is unknown. Further studies on the relationship between M2 and M3 are reported by Crawford and Mark (1982) and Bosbyshell et al. (1999).

Peak metamorphic temperatures recorded by the Wissahickon rocks adjacent to the Wilmington Complex are estimated by geothermobarometry to be $700\pm 50^{\circ}\text{C}$ at 4.5 ± 1 kb (Crawford and Mark, 1982; Calem, 1987; Plank, 1989; Alcock, 1989; Alcock and Wagner, 1995; Bosbyshell et al., 1999).

Boundaries. The Wissahickon Formation extends westward from the contact with the Wilmington Complex and is contiguous with the Wissahickon Formation as shown on the Pennsylvania Geologic Map (Berg, 1980) and the area mapped in northeastern Maryland as pelitic schist, pelitic schist with amphibolite, and pelitic gneiss (Higgins, 1990).

Reference Section. The type section for the Wissahickon Formation is in Fairmont Park, Philadelphia, Pennsylvania. The outcrops along the Red Clay Creek in Brandywine Springs Park and near Mt. Cuba, Delaware² have been selected as Delaware reference sections. Lithologies at Brandywine Springs Park include quartzofeldspathic migmatites and garnet-orthopyroxene-bearing quartzites (Cc12-a, Cc12-c). Large outcrops along the creek at Mt. Cuba display typical pelitic, psammitic, and amphibolite lithologies (Bc32-b, Bc32-c, and Bc32-q). Unusually large sillimanite nodules occur in the pelitic rocks (Bc32-d).

Lithology. The major lithologies in the Wissahickon Formation are pelitic and psammitic gneisses and amphibolites. Contacts between the pelitic and psammitic gneisses are gradational with the psammitic gneisses being the most abundant. These two lithologies may be considered end members in a continuous series of bulk rock compositions from dominantly pelitic to dominantly psammitic. Metamorphic differentiation in the pelitic and psammitic

rocks has separated quartzofeldspathic layers from layers rich in biotite, sillimanite, and garnet, thus making flaser and ribbon textures common. Sillimanite is concentrated in the pelitic lithologies as a matrix mineral, in flattened nodules that vary from 0.25 to 1 inch in diameter, in veins approximately 0.25 in thick, and as large fibrous clumps from 2 to 3 ft in diameter.

Brandywine Springs Park is renowned for the large boulders of sillimanite that can be found along the banks of the Red Clay Creek and its tributaries. We have not seen the sillimanite boulders in outcrops but assume they formed in the aluminous pelitic schists that occur throughout the Park. Because of this occurrence, sillimanite was designated by the Delaware General Assembly as the state mineral. A large sillimanite boulder is on display in the Delaware Geological Survey building in Newark. Blue-gray sillimanite in clusters up to 10 inch in diameter are found along the west shore of Hoopes Reservoir near the ultramafic lens.

In most cases primary sedimentary structures have been obliterated by deformation, metamorphic differentiation, and partial melting; however, in a few outcrops the psammitic layers exhibit an inverse grading, which may reflect primary graded bedding. Quartz-rich psammitic layers alternate with biotite-sillimanite rich layers on a scale of 3 to 4 in, and may represent deposition by submarine turbidity currents.

Granitic pegmatites of various sizes, compositions, and ages are ubiquitous. One pegmatite north of Newark, Delaware, is large enough to be mapped (Plate 1). This pegmatite is coarse- to very coarse-grained with tourmaline crystals locally. Where outcrop is present, pegmatite is tabular, undeformed, and concordant with the regional trend of the underlying Wissahickon Formation. Subhorizontal foliation in the pegmatite body occurs along the bottom contact with Wissahickon gneisses.

Amphibolite layers are concentrated in the psammitic gneiss, and the contacts between the gneiss layers and the amphibolite layers are always sharp. Several hundred feet south of the Hockessin-Yorklyn Valley along the tracks of the Wilmington and Western Railroad, a series of amphibolite layers 5 to 31 in thick are separated by 2 to 11 in-thick micaceous layers (Bb25-c). R. C. Smith (personal communication, May 2000) suggested the micaceous layers are similar to those along the White Clay Creek in Pennsylvania, and they may represent metatuffs.

Petrography. The pelitic and psammitic gneisses contain biotite, quartz, and plagioclase (oligoclase to andesine). Muscovite, sillimanite, orthoclase, biotite, garnet, cordierite, and spinel vary systematically with metamorphic grade. The common accessory minerals are iron-titanium oxides, zircon, apatite, and sphene. The quartz grains are recrystallized into subgrains with sutured grain boundaries and are elongated parallel to the foliation. In contrast, the plagioclase grains are equant and fractured with minor alteration to sericite. Albite, pericline, and combined albite and pericline twins are common. Biotite laths, pleochroic in shades of red-brown, are usually oriented parallel to the foliation. Sillimanite grains show a regional progression from domi-

² The Delaware Wissahickon Formation reference section is on property owned by Mrs. Lamont du Pont Copeland. Ultimately the property will be turned over to the Mount Cuba Foundation and opened to the public.

nantly fibrolite in the west to a combination of fibrolite, acicular clusters, and large prisms in the east.

Garnets show diversity in size, shape, inclusions, and zoning styles. Most common are the large equidimensional garnets that are texturally zoned by variations in inclusions. Chemical zoning is preserved in garnets in the western part of the map area; however, it has been erased by diffusion of cations in garnets in the east near the Wilmington Complex. A detailed description of the garnets can be found in Plank (1989) and Alcock (1989).

The amphibolite is fine- to medium-grained and composed of subequal amounts of plagioclase and hornblende with or without clinopyroxene. In the areas of highest metamorphic grade the hornblende is pleochroic in shades of green, and accessories are restricted to iron-titanium oxides. At lower metamorphic grade, the pleochroism is present in shades of green and blue green, and accessory phases include sphene and clinozoisite/epidote. Hornblende grains are usually elongated to form a weak foliation. Tables of modes can be found in Woodruff and Plank (1995), Plank (1989), and Alcock (1989).

A rare contact between a pelitic layer of the Wissahickon Formation and a mafic layer of the Brandywine Blue Gneiss is exposed in Brandywine Creek State Park (Bd12-d). The Wissahickon occurs as a thin, 6-in-thick migmatitic layer with leucosomes containing quartz, orthoclase, and plagioclase, and melanosomes containing small euhedral garnets plus a few wisps of sillimanite and biotite. Although the composition of the fluid phase is unknown, this assemblage probably represents the highest metamorphic conditions in the Wissahickon Formation. A 2-ft-thick mafic layer on the east side of the pelitic layer is fine-grained and composed of 45 percent plagioclase, 45 percent clinopyroxene, 7 percent brown hornblende, and 3 percent quartz with large porphyroblasts of "red" biotite (in polarized light) and clinopyroxene. The rock is weakly foliated, and porphyroblasts lie athwart the foliation. The layering is vertical and strikes N40°E.

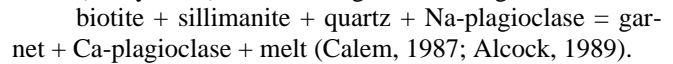
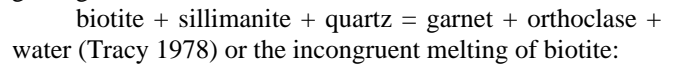
Metamorphism. The Wissahickon Formation in the map area was metamorphosed to the amphibolite facies. The intensity of metamorphism increases from west to east as muscovite and quartz react to form sillimanite and orthoclase and the metamorphism progresses across the second sillimanite isograd (Hager, 1976; Wagner and Srogi, 1987; Plank, 1989, and Alcock, 1989). The second sillimanite isograd is based on the first appearance of the pair orthoclase and sillimanite in pelitic rocks and is due to the reaction:



Muscovite persists in the metapelites even after the first appearance of orthoclase. This phenomenon is documented in other high-grade metamorphic terranes and is attributed to continuous reactions involving Na and K in muscovite and Na and Ca in plagioclase (Evans and Guidotti, 1966; Tracy, 1978; and McLellan, 1985).

Thus, the lowest grade assemblage of quartz, biotite, plagioclase, orthoclase, sillimanite, muscovite, and ilmenite \pm garnet occurs in the southwestern portion of the Wissahickon Formation. Toward the northeast, muscovite gradually disappears from the assemblages and is missing from the rocks east of Red Clay Creek. At the highest grades of metamorphism near the Brandywine Blue Gneiss, iron-

rich biotite is unstable and breaks down to form garnet suggesting a reaction such as:



Cordierite and hercynitic spinel occur in the melanosomes of some of these high-grade migmatitic rocks adjacent to the Brandywine Blue Gneiss. According to Calem (1987) these minerals form as a result of incongruent melting of biotite-sillimanite and biotite-garnet-sillimanite assemblages. In most cases, fibrous sillimanite and biotite cluster along the edges of the cordierite porphyroblasts.

Garnets, which are present in the pelitic rocks throughout the Wissahickon, vary in size, shape, texture and chemistry and can be used to track the metamorphic progression from west to east. Detailed description of the garnet and garnet-biotite relationships can be found in Calem (1987), Plank (1989), Alcock (1989) and Alcock and Wagner (1995).

Peak metamorphic temperatures estimated by means of various garnet-biotite geothermometers increase from 620°C west of Newark to 750°C east of the Red Clay Creek. Margin of error for the geothermometers is $\pm 50^\circ\text{C}$. Pressures estimated by various geobarometers based on the exchange of calcium between garnet and plagioclase vary from 4 to 7 kilobars. The geobarometers are poorly constrained with accuracy of >1 kilobar (Plank, 1989; Alcock, 1989; Alcock and Wagner, 1995).

Inferred peak metamorphic temperatures increase toward the Wilmington Complex. This suggests the Wilmington Complex was the heat source for the metamorphism. The alternative explanation that deeper, and hence hotter, crustal levels are exposed in the eastern part of the map area is not confirmed by the geobarometry, which, although poorly constrained, indicates deeper burial toward the northwest not toward the Wilmington Complex (Plank, 1989; Alcock, 1989; Alcock and Wagner, 1995).

Higher-pressure, kyanite-staurolite-muscovite assemblages have been described at a few locations in the band of Wissahickon surrounding the Brandywine Blue Gneiss in Pennsylvania (Crawford and Mark, 1982; Calem, 1987; Bosbyshell et al., 1999). The development of these overprinting assemblages is variable because it depends upon the amount of deformation and availability of water.

Deformation. The rocks are complexly folded by multiple deformational events. We can identify four or five events that are followed by faulting as the rocks cooled and became brittle. The earliest folding event is preserved in the pelitic and psammitic gneisses as intrafolial folds (D1). The presence of small-scale refolded folds in the gneiss suggests a second event (D2). The dominant deformational event folded the units into westward verging thrust nappes and also folded the compositional layering into isoclinal folds (D3). The axial planes and limbs of the isoclinal folds are parallel and consistently strike between N30°E and N60°E with the most common strike being N40°E. Northeast of Red Clay Creek, most foliations dip steeply to the northwest. Southwest of the creek the foliations dip steeply to the southeast and become less steeply inclined to the northwest away from the Wilmington Complex. In addition, the plunge

of the folds varies from 0° to 90° to the NE and SW, suggesting complex fold patterns. The metasedimentary rocks that occur within the Faulkland Gneiss have a different orientation and strike between north-south and N20°E and dip at a moderate angle to the southeast (Plate 1). Later folds are indicated by the map pattern that shows broad warps around a northeast-southwest axis (D4). In addition to the folding events, numerous shear zones and both brittle and ductile faults occur within the Wissahickon Formation.

Geochemistry. Smith and Barnes (1994) collected 12 samples of Wissahickon amphibolites from the White Clay Creek Valley and 7 samples from an area near Kennett Square for chemical analysis. They were the first to use chemical data to recognize two amphibolite types within the Wissahickon Formation: Type 1 (Kennett Square amphibolites, Smith and Barnes, 1994) that resemble N-MORBs or E-MORBs, and type 2 (White Clay Creek amphibolites, Smith and Barnes, 1994) that originated as intraplate basalts (Plank et al., in press).

Age. The age of the Wissahickon Formation has been a major geological controversy for nearly a century. The best estimate for the age is between late Proterozoic and Ordovician (Higgins, 1972; Wagner and Srogi, 1987; Drake et al., 1989). Thermal Ionization Mass Spectrometry (TIMS) analysis on grains of monazite from the Wissahickon Formation adjacent to the Brandywine Blue Gneiss in Pennsylvania yielded U-Pb ages of 418 to 411 Ma recording the cooling from high temperature conditions (Bosbyshell et al., 1998).

Ultramafic Lens

Definition. A lens of ultramafic and mafic rocks, approximately 1.3 miles long and 0.5 miles wide, is exposed west of Hoopes Reservoir in the Wilmington North and Kennett Square U. S. Geological Survey 7.5-minute topographic quadrangles. The rocks, once peridotite, pyroxenite, and gabbro, have been metamorphosed to serpentinite, monomineralic amphibolite, and a hornblende-plagioclase amphibolite (personal communication, R. C. Smith, May 5, 2000). The lithologies are similar to those described for the Baltimore Mafic Complex, Maryland (Southwick, 1970; Sinha and Hanan, 1987; Hanan and Sinha, 1989; and Drake, 1993).

Boundaries. The lens of ultramafic and mafic rocks is enclosed within the Wissahickon Formation west of Hoopes Reservoir. The contacts are not exposed.

Type Section. The type section for the ultramafic lens is designated as the rocks that crop out on the hillside west of Hillside Mill Road opposite Hoopes Reservoir (Bc33-q, Bc33-r, Bc33-s, Bc33-t, Bc33-k, Bc33-m).

Lithology. Three lithologies representing a gross east to west stratigraphy can be distinguished in the field. In the east, basal serpentinites occur as highly fractured, variegated greenish rocks with an orange-weathering surface. Locally, the serpentinite is associated with thin layers of talc and magnesite. Chlorite occurs as sheets, flakes, or books up to 1.25 inches. Cummingtonite/anthophyllite amphibolite occurs west of the serpentinite. The amphibolite is coarse-grained, and composed of interlocking grains of light colored, fibrous amphiboles, most likely magnesium-rich cummingtonite and/or anthophyllite plus possible clinoclhor.

Farther west, the rocks become finer grained and darker as hornblende replaces the cummingtonite and anthophyllite to create the hornblendites. West of the hornblendites the rocks are coarse-grained metamorphosed gabbros composed of hornblende and plagioclase.

Petrography. Petrographic observations and mineral identifications were carried out in the field and on hand samples. Time constraints on this project have not permitted thin sections to be made and studied.

Metamorphism. The ultramafic and mafic rocks were originally peridotite, pyroxenite, and gabbro. The peridotite has been metamorphosed to serpentinite, the pyroxenite to amphibolite composed of ortho-amphibole or hornblende, and the gabbro to a hornblende/plagioclase amphibolite. Metamorphism is retrograde and probably a result of the same event that caused the amphibolite facies metamorphism in the Wissahickon Formation.

Deformation. Where exposed the serpentinite is highly fractured. The metapyroxenites and metagabbros occur as coarse-grained, massive boulders. The map pattern suggests deformation is similar to that in the surrounding Wissahickon Formation (Plate 1).

Wilmington Complex (herein redefined)

Previous Definition. The Wilmington Complex was originally defined by Ward (1959) to include the igneous and metamorphic rocks between Newark, Delaware, and Chester, Pennsylvania. The principal units were granulite facies banded gneisses, amphibolite facies gneisses that occur southwest of the banded gneisses, the Bringhurst Gabbro, the Arden granite, and a granodiorite, correlated with the Port Deposit granodiorite in Maryland. Ward studied the Iron Hill Gabbro but did not include it within the complex. Ward's (1959) map clearly indicates that the complex extends well into Cecil County, Maryland, an area currently mapped as James Run Formation by Higgins (1972), Higgins and Conant (1986), and Higgins (1990). The present geologic maps of Delaware (Woodruff and Thompson, 1972, 1975) generally followed Ward's boundaries.

Subsequent to Ward's work and the completion of the geologic maps by Woodruff and Thompson (1972 and 1975), several changes have been proposed. The size and shape of the Bringhurst and Arden plutons have been remapped (Wagner and Srogi, 1987; Srogi, 1988), and the composite nature of the Arden pluton has been recognized (Srogi and Lutz, 1997). Ward's amphibolite facies gneisses located southwest of the banded gneiss were placed in the James Run Formation (Pickett, 1976; Hager, 1976; Thompson, 1979). Higgins (1972) extended formational names from the southwestern Maryland Piedmont into Cecil County and considered the layered rocks of the Wilmington Complex to be correlative with the James Run Formation. In addition, he traced the rocks of the Gilpins Falls Member and the Big Elk Member of the James Run Formation for over one half mile into Delaware (Higgins, 1990).

Except for Higgins (1990), the changes to the Wilmington Complex have been published on small-scale generalized maps that differ in their placement of the Wilmington Complex boundaries. For example, Pickett (1976), Hager (1976), and Thompson (1979) place Ward's amphibolites in the James Run Formation. Wagner and

Srogi (1987), Srogi (1991), and Wagner et al. (1991) place some of Ward's amphibolites in the James Run Formation and some in a redefined Wilmington Complex.

New Definition. On the bases of detailed mapping by the authors, new geochemical data (Plank et al., in press), and U-Pb zircon ages (John N. Aleinikoff, U.S. Geological Survey, personal communication, 2000), we preserve the name Wilmington Complex and herein redefine it to include all rocks associated with an early Paleozoic magmatic arc. We propose that the Wilmington Complex is a fragment of one of the early Paleozoic arcs identified along the Appalachians from Georgia to Newfoundland. The Wilmington Complex rock units extend across the Newark West, Newark East, Wilmington South, Wilmington North, and Marcus Hook quadrangles.

As now defined, the units in the Wilmington Complex are:

Metavolcanic Units

Windy Hills Gneiss (formerly amphibolite, Ward, 1959)

Faulkland Gneiss (formerly amphibolite, Ward, 1959)

Rockford Park Gneiss (formerly banded gneiss, Ward, 1959)

Metaplutonic Units

Felsic units

Brandywine Blue Gneiss (formerly part of banded gneiss, Ward, 1959)

Christianstead Gneiss (formerly Port Deposit granodiorite, Ward, 1959)

Barley Mill Gneiss

Gabbroic units

Montchanin Metagabbro (formerly amphibolite, Ward, 1959)

Mill Creek Metagabbro

Undeformed Plutons

Arden Plutonic Supersuite

Ardentown Granitic Suite (formerly Arden granite, Ward, 1959)

Perkins Run Gabbronorite Suite
biotite tonalite

Bringhurst Gabbro

Iron Hill Gabbro

Windy Hills Gneiss (herein named)

Definition. The metavolcanic and metavolcaniclastic rocks of early Paleozoic age that occur along the Fall Line in Delaware are herein named the Windy Hills Gneiss. The unit is composed of interlayered amphibolite, felsic gneiss, biotite gneiss, and minor metasediments. It has been intruded by local plutons that are too small to map at the scale of Plate 1, and by one mappable pluton, the Christianstead Gneiss. In Delaware, the Windy Hills Gneiss is located within the Newark West, Newark East, and Wilmington South quadrangles.

Historical Background. The Windy Hills Gneiss was formerly assigned by Ward (1959) to the Wilmington Complex as Amphibolite A and B. Pickett (1976) and Thompson (1979) extended the James Run Formation into Delaware encompassing some of the area previously mapped as Wilmington Complex by Ward (1959). In extending the James Run Formation, Pickett and Thompson essen-

tially redefined the extent of both the Wilmington Complex as mapped by Ward (1959) and the James Run Formation as mapped by Higgins (1972).

Southwick and Fisher (1967) defined the James Run Gneiss as the interlayered quartz amphibolite and biotite-quartz plagioclase gneiss exposed along James Run in Harford County, Maryland, and suggested a volcanic and volcanoclastic origin for these rocks. Southwick (1969) noted the similarities of the James Run Gneiss to the Baltimore paragneiss (Hopson, 1964), parts of the Cecil County volcanic complex (Marshall, 1937), and some of the Wilmington Complex (Ward, 1959).

Higgins (1971, 1972) changed the name of the Maryland rocks from the James Run Gneiss to the James Run Formation and formally defined the unit to include all of the closely-associated, apparently contemporaneous metavolcanic and metavolcaniclastic rocks that crop out in the northeastern Maryland Piedmont. He also included the Cecil County volcanic complex in the James Run Formation, placed the James Run Formation in the Glenarm Series, and proposed formal correlation with the Chopawamsic Formation in Virginia.

Higgins (1990) divided the James Run Formation in Cecil County, Maryland, into seven formally named members, the Principio Furnace, Frenchtown, Little Northeast Creek, Gilpins Falls, Big Elk Creek, Principio Creek, and Happy Valley Branch members, and one felsite lens of limited extent. He removed the James Run Formation from the Glenarm Group because he considered the contact between the two units to be a thrust fault. He also extended the Big Elk Member from Cecil County, Maryland, into Delaware for over one half a mile. We cannot physically trace the Big Elk across the Delaware-Maryland boundary because of the intervening Christianstead Gneiss; therefore, we have named the interlayered mafic and felsic lithologies on the east side of the Christianstead Gneiss the Windy Hills Gneiss. We assign it to the Wilmington Complex because the age of Windy Hills Gneiss is reported to be 481 ± 4 Ma, similar to the ages reported for the other units in the Wilmington Complex (John N. Aleinikoff, U. S. Geological Survey, personal communication, 2000). The age of the James Run Formation in Baltimore, Maryland, and the Chopawamsic Formation in Virginia is reported by Horton et al. (1998) to vary between 454 ± 5 Ma and 464 ± 5 Ma. Thus, there is a significant difference in age between the James Run in Baltimore and the Windy Hills Gneiss in Delaware. We propose that the volcanic rocks in Cecil County may be part of the Wilmington Complex rather than of the James Run Formation in the Baltimore area, but without ages for the Cecil County rocks we cannot prove this.

Boundaries. The metavolcanic and metavolcaniclastic rocks of the Windy Hills Gneiss occur in a belt that parallels the Fall Line from the contact with the Christianstead Gneiss in the west to the Brandywine Blue Gneiss in the east. The southern boundary of the unit and much of the unit itself is overlapped by sediments of the Coastal Plain; therefore, much of our information on this unit comes from cores recovered from drilling bedrock under the Coastal Plain. The northern contact with the Wissahickon Formation seems to be concordant with the regional strike and with the strike of the foliations in both units; however, the contact is not

exposed. The northeast contact with the Faulkland Gneiss may be gradational, but it is also not exposed.

Reference Section. The type section for the Windy Hills Gneiss is along White Clay Creek under the Windy Hills Bridge on Delaware Route 2, Kirkwood Highway (Cb42-c).

Lithologies. Interlayered amphibolite, felsic gneiss, and biotite-quartz-plagioclase gneiss are exposed throughout the Windy Hills Gneiss. The scale of layering varies from >6 inches to several feet. The contacts between units are sharp, with occasional thin granitic layers at contacts between the amphibolite and felsic layers. These granitic layers may be fluid-induced melts. Medium- to coarse-grained pegmatites cross cut the layering.

Megascopically there are two varieties of biotite-quartz-plagioclase gneiss: (1) a coarse-grained variety with compositional layering and pods and veins of pegmatite, and (2) a fine-grained weakly foliated variety. Contacts between the two varieties are sharp with large poikiloblastic garnets commonly concentrated along the contacts.

A two-pyroxene felsic gneiss interlayered with clinopyroxene-rich amphibolite was identified in cores drilled adjacent to the railroad track on Red Mill Road (Schenck and Plank, 1995). This rock lithologically and petrographically resembles the Brandywine Blue Gneiss. This enigmatic occurrence of two-pyroxene gneiss within the Windy Hills Gneiss suggests the relationship with the Brandywine Blue Gneiss may be more complex than we have shown on Plate 1.

Petrography. The composition of amphibolites in the Windy Hills Gneiss varies between 5 and 20 percent quartz, 20 and 50 percent plagioclase, and 26 and 50 percent hornblende with or without clinopyroxene, orthopyroxene, and biotite. Accessory minerals are sphene, and iron titanium oxides. Hornblende is pleochroic in shades of green in rocks exposed in the eastern parts of the unit, and blue-green to light green in rocks to the west.

The felsic gneisses contain 85 to 90 percent quartz and plagioclase, with or without minor microcline, and less than 10 percent of mafic minerals biotite, hornblende, or orthopyroxene. Clinzoisite, sphene, garnet and iron-titanium oxides are present as minor phases. Small fibers of sillimanite occur along the grain boundaries of a few plagioclase grains; however, sillimanite is not an important phase in these rocks. Microcline is distinctive with crosshatch twinning and quartz and feldspar myrmekite along grain boundaries. Twinning on the albite, pericline, and Carlsbad laws can be observed in plagioclase grains.

The minerals in the biotite gneiss are plagioclase, quartz, and biotite with or without microcline. The plagioclase ranges from 35 to 45 modal percent and is always more abundant than quartz. The quartz varies between 25 and 35 percent, biotite between 15 and 30 percent, and microcline between 0 and 20 percent. Clinzoisite, iron-titanium oxides, and sphene are accessory phases. Plagioclase, normally andesine, may be antiperthitic. Accessories are zircon, apatite, and sometimes allanite. Modes are listed in Schenck and Plank (1995).

Metamorphism. The amphibolite changes from plagioclase, iron-titanium oxide, and green-brown hornblende in the eastern part of the Windy Hills Gneiss to plagioclase,

iron-titanium oxide, sphene, clinzoisite, and blue-green hornblende in the western part. From this change we infer that metamorphic grade recorded by the mineral assemblages in the Windy Hills Gneiss increases eastward toward the Brandywine Blue Gneiss (Bucher and Frey, 1994).

Deformation. The Windy Hills Gneiss is characterized by compositional layering that normally dips steeply southeast between 80° and 90°. The strike of the layering shows a gradual change from N10°E in the northeast to N80°E in the southwest. Folding in the Windy Hills Gneiss in Delaware is complex and is similar to that described by Higgins (1973) in the James Run Formation of Cecil County, Maryland.

Geochemistry. Three mafic samples of Windy Hills Gneiss were collected for chemical analysis. Both in the field and petrographically these rocks resemble the mafic rocks in the Rockford Park Gneiss; however, trace element concentrations and Rare Earth Element (REE) patterns differ significantly, indicating the two units originated from a different magma source. REE patterns from the Windy Hills mafic rocks are almost flat, and abundance is medium to low, similar to island arc tholeiites (Pearce 1982, 1983).

Age. Sensitive high-resolution ion microprobe (SHRIMP) data indicate a U-Pb zircon age of 481±4 Ma for the igneous crystallization of a sample of felsic biotite-gedrite-cordierite gneiss (Cb35-a) from the Windy Hills Gneiss (John N. Aleinikoff, U. S. Geological Survey, personal communication, 2000).

Faulkland Gneiss (herein named)

Definition. Metavolcanic and metavolcaniclastic rocks composed of interlayered amphibolite, quartz amphibolite, and felsic gneiss that are interlayered with metasedimentary rocks are herein named the Faulkland Gneiss. We assign the metasediments that are extensive enough to be mapped at 1:24,000 scale to the Wissahickon Formation. The gneiss is located within the Newark East, Wilmington South, Kennett Square, and Wilmington North quadrangles.

Historical Background. The histories of the Faulkland Gneiss and the Windy Hills Gneiss are similar. The rocks now assigned to the Faulkland Gneiss were originally identified by Ward (1959) as Amphibolite A of the Wilmington Complex. Later Pickett (1976) and Thompson (1979) extended the James Run Formation into Delaware encompassing all of the Windy Hills Gneiss and part of the present Faulkland Gneiss. We have removed the Faulkland Gneiss and the Windy Hills Gneiss from the James Run Formation because the new U-Pb ages determined during this study indicate those units are significantly older than the rocks of the type section of the James Run Formation near Baltimore.

Boundaries. Along its southern boundary, the Faulkland Gneiss is in contact with the Windy Hills Gneiss. The contact is defined by float in streambeds. The northern boundary of the Faulkland Gneiss is constrained by outcrops and float of the Montchanin Metagabbro. The actual contact is not exposed. The eastern margin of the Faulkland Gneiss is adjacent to the Brandywine Blue Gneiss; however, it is concealed by Rt. 141. To the west the Faulkland Gneiss is intruded by the Barley Mill Gneiss. The Faulkland Gneiss and the metasediments of the Wissahickon Formation are

intimately associated; however, the nature of the relationship is unknown because the contacts are not exposed.

Type Section. The rocks that crop out along the west bank of the Red Clay Creek between Lancaster Pike (Rt. 48) southeast to Kirkwood Highway (Rt. 2) are designated the type section for the Faulkland Gneiss. Outcrops Bc52-d, Cc12-n, Cc12-a, Bc53-f, and Cc22-c display the more common lithologies in the Faulkland Gneiss.

Lithology. The Faulkland Gneiss is characterized by diverse lithologies that we consider to be of volcanic and volcanoclastic origin. In many cases, the lithologies grade into one another; however, the identifiable lithologies are quartz amphibolite, amphibolite, cummingtonite amphibolite, felsic gneiss, and rare hornblendite. The size of the hornblende grains in the amphibolite and quartz amphibolite vary from fine to coarse, and folded quartz-filled fractures are usually present. The amphibolite sometimes contains large, 0.25 to 0.5 in, poikiloblasts of greenish clinopyroxene. The cummingtonite amphibolite is coarse-grained with large poikiloblastic garnets concentrated along the contact with other units. The felsic gneiss is rarely seen in outcrop but is common in streambed gravels.

In addition, we assign to the Wissahickon Formation rocks of clearly sedimentary origin, such as garnet- and orthopyroxene-bearing quartzite, aluminous pelitic schist, pelitic gneiss, psammitic gneiss, and migmatite, that are intimately mixed with amphibolite-bearing units presumably of volcanic origin.

The Faulkland Gneiss contains a number of distinctive textures the most common being 0.125 in to 0.75 in magnetite grains surrounded by quartzo-feldspathic mantles. Hager (1976) and Thompson (1979) noted their occurrence and referred to this texture as “bright eyes.” Normally they are round and randomly spaced; however, they have been observed as ellipsoids elongated in the foliation. Studies in Precambrian terranes in Colorado (Trumbull, 1988) and in the Baltimore Gneiss in the Towson dome, Maryland (Olsen, 1999), referred to similar segregations as flecked gneisses or flecky gneisses. Both authors conclude that the “fleck” or “bright eye” is formed by metamorphic differentiation driven by chemical potential gradients between different mineral assemblages.

Two types of garbenschiefer are present in the Faulkland Gneiss: Type 1 is characterized by stellate, radiating aggregates of hornblende along foliation or fracture surfaces; type 2 consists of bundles of needles of either hornblende, cummingtonite, or gedrite that branch out and form bow-tie structures about the size of caraway seeds (Barker, 1990). The bow tie structures occur randomly throughout the amphibolite rather than along the foliation surface. The randomly orientated garbenschiefers may be products of thermal metamorphism following regional metamorphism, as the porphyroblasts grow across an early foliation (Spry, 1969), or it may be that recrystallization simply outlasted deformation.

Finally, in addition to the large green clinopyroxene porphyroblasts, elongated spots of greenish clinopyroxene are common within black amphibolites. We have not found references to this texture but postulate that during metamorphism metasomatic fluids infiltrated irregularly into the basalt layers. Some clinopyroxene grains were metamor-

phosed to hornblende, whereas others remain as relict pyroxene grains.

Petrology. The amphibolites contain subequal amounts of hornblende and plagioclase, whereas the quartz amphibolites and hornblende gneisses contain 10 to 25 percent quartz, 30 to 60 percent plagioclase, and 35 to 60 percent hornblende (Howard, 1986; Schenck and Plank, 1995). Orthopyroxene and clinopyroxene commonly occur with the hornblende. Hornblende is pleochroic in shades of green or brown. In rocks where pale-green cummingtonite is the only amphibole, it occurs with subequal amounts of plagioclase and sometimes with large poikiloblastic garnets.

The felsic rocks are composed of varying amounts of plagioclase and quartz with <10 percent mafic minerals. The weakly aligned, mafic minerals are orthopyroxene, hornblende, biotite, or cummingtonite. In all samples, plagioclase is twinned on the albite, pericline, and Carlsbad laws and averages An₄₀ in composition. Deformational features observed in thin section are partial twinning in plagioclase, and undulatory extinction, development of subgrains, and lobate grain boundaries in quartz.

Metamorphism. The metamorphic grade is uniform throughout the Faulkland Member. Mineral assemblages indicate that peak metamorphism was at upper amphibolite facies with some overprinting indicated by the retrograde textures.

Deformation. Vertical to slightly southeast-dipping isoclinal and crinkle folds are common in the Faulkland Gneiss. Locally the folds in the Faulkland Gneiss and the Wissahickon Formation are concordant. The strike of lineations, foliations, and axial planes of the folds vary between north-south and N20°E.

Age. SHRIMP data indicate a U-Pb zircon age of 482±4 Ma for the igneous crystallization of felsic gneiss that contains plagioclase and quartz plus <10 percent biotite and cummingtonite (Bc53-f) (John N. Aleinikoff, U. S. Geological Survey, personal communication, 2000).

Christianstead Gneiss (herein named)

Definition. The Christianstead Gneiss is the name given to the moderately deformed coarse-grained, granodioritic gneiss that underlies the City of Newark, Delaware, and the area to the west. The unit is located within the Newark West and Newark East quadrangles. Most of the pluton is covered by sediments of the Atlantic Coastal Plain; however, in the 1990s during the construction of two communities west of Newark, Christianstead and West Branch, the granodioritic gneiss was exposed.

Historical Background. Ward (1959) first identified granodiorite from small bedrock exposures near the Delaware-Maryland border. He found deeply weathered specimens of what appeared to be granodiorite in drill holes in the Coastal Plain sediments around Iron Hill and from the bottom of deep wells (800 ft) as far south and east as Delaware City. The granitic rocks in the wells suggested to him that the granodiorite surrounds the Iron Hill stocks. Our data can not confirm nor disprove his reports.

In addition, he correlated the granodiorite in Delaware with the Port Deposit granodiorite in Maryland. However, because the Port Deposit and the Christianstead granodiorites have intruded different units and are separated geo-

graphically by most of Cecil County, we have mapped the granodiorite in Delaware as a separate body. Woodruff and Thompson (1972) identified this Delaware body of rock as a granitic pluton and did not give it a formal name.

South of the James Run Formation in Cecil County, Maryland, Higgins and Conant (1986) mapped a large felsic pluton called the gneiss at Rolling Mill. The gneiss at Rolling Mill is composed of muscovite, biotite, plagioclase, and quartz with tiny garnets, minor clinozoisite, and no microcline. Based on Higgin's report (1990) and our samples of Christianstead Gneiss (Ca53-b), the gneiss at Rolling Mill and the Christianstead Gneiss are not correlative. We have mapped the Christianstead Gneiss up to the Delaware-Maryland border, suggesting the pluton may extend a short distance into Maryland; conversely the gneiss at Rolling Mill may extend into Delaware south of the Christianstead Gneiss. There are no outcrops to constrain the boundaries of these units.

Boundaries. The Christianstead Gneiss intrudes the Windy Hills Gneiss on the east, and along its southern margin the pluton is covered by Coastal Plain sediments. To the north the pluton abuts the Wissahickon Formation.

Type Section. The Christianstead Gneiss is defined as a lithodemic unit within the Wilmington Complex. The weakly foliated granodioritic gneiss, exposed at the corner of Hidden Valley Road and Haywood Court in the community of Christianstead is designated as the type locality (Ca44-d2). Although the original outcrops are no longer present, many boulders of this unit are preserved in the landscaping in this community.

Lithology. The Christianstead pluton is a moderately deformed, weakly metamorphosed coarse-grained granodiorite with minor inclusions of layered amphibolite. The individual grains of quartz, plagioclase, and microcline are large enough to be identified with the naked eye. Biotite grains are aligned and define a weak foliation that becomes more pronounced near the contact with the Wissahickon Formation. The foliation strikes N70°W, approximately parallel to the northern boundary of the pluton, and dips to the southeast at 45°. Along Hidden Valley Road in Christianstead an enclave of fine-grained, layered amphibolite, approximately 20 ft long and 5 ft thick, is enclosed within the granodiorite. This outcrop is now covered by a house and lawn.

Granitic pegmatites, some 60 to 70 feet thick, are associated with the granodiorite. Beryl crystals 1 to 3 in long and euhedral tourmaline crystals 6 to 8 in long were collected from one of these pegmatites exposed during construction of the development adjacent to Christianstead, West Branch.

Petrography. The gneiss is granitic to granodioritic in composition. A sample from Hidden Valley Road in Christianstead contains 39 percent quartz, 35 percent plagioclase, 23 percent microcline, and 3 percent biotite. Accessory phases are garnet, clinozoisite, muscovite, sphene, and zircon. Myrmekite of quartz and feldspar are common. Near the contact with the Wissahickon Formation, the rock is more biotite-rich, containing 35 percent plagioclase, 33 percent quartz, 17 percent microcline, and 15 percent biotite. Accessory minerals in this sample are iron-titanium oxides, clinozoisite, apatite, allanite and sphene. Quartz in some samples is recrystallized to a mosaic

of medium-sized grains with no undulatory extinction. Microcline is perthitic with cross-hatch twinning. Biotite is pleochroic in shades of brown and commonly has a distinct preferred orientation. Strain is recorded by deformation twins in plagioclase and undulatory extinction in the largest quartz grains. Textures are allotriomorphic granular but modified by deformation and recrystallization.

The fine-grained amphibolite enclave contains 56 percent hornblende, 39 percent plagioclase, and 5 percent quartz. Sphene and allanite are accessories. Green pleochroic hornblende grains are elongated and aligned to define the foliation. Plagioclase grains are elongated with albite and pericline twinning.

Metamorphism. Mineral assemblages of biotite, microcline, quartz, and plagioclase indicate the rocks were metamorphosed to the amphibolite facies.

Deformation. Biotite grains are aligned and define a weak foliation that becomes more pronounced near the contact with the Wissahickon Formation. The foliation strikes N70°W, approximately parallel to the northern boundary of the pluton and dips to the southeast at 45°.

Age. SHRIMP U-Pb zircon ages for the Christianstead Gneiss are 488±8 Ma (John N. Aleinikoff, U. S. Geological Survey, personal communication, 2000). The zircons were recovered from a sample of the granodiorite (Ca44-d2) collected during construction of the community of Christianstead. The sample contained only one population of elongate, prismatic (igneous) zircons.

Barley Mill Gneiss (herein named)

Definition. The Barley Mill Gneiss includes variably deformed felsic gneisses of tonalitic, trondhjemitic, and granodioritic composition, amphibolites, and minor hornblendites. It is recognized as a composite pluton that intrudes the Faulkland Gneiss and the Wissahickon Formation, and is located within the Kennett Square quadrangle west of the city of Wilmington.

Historical Background. Ward and Groot (1957) were the first to map felsic gneiss with the composition of a granodiorite or a diorite in the vicinity of Wooddale. The felsic gneiss was mapped as an elongate body that intruded along the contact between the Wissahickon Formation and the Wilmington Complex. Hager (1976) and Thompson (1979) reported the gneiss has the composition of a quartz diorite, and assigned the gneiss to the James Run Formation. Later, Thompson (1981) and Howard (1986) suggested that the unit may be a metasedimentary melange and correlated it with the Sykesville Formation in Maryland. The Sykesville Formation is identified as biotite-plagioclase-quartz gneiss that is characterized by modal quartz greater than plagioclase and numerous inclusions of biotite schist, amphibolite, serpentinite, and quartz. It has been interpreted to be a submarine slide mass or a sedimentary melange (Hopson, 1964; Southwick and Fisher, 1967; Southwick, 1969; Higgins, 1972; Drake and Morgan, 1981; Higgins, 1990). The Barley Mill Gneiss is hornblende-biotite-quartz-plagioclase gneiss, with modal plagioclase greater than modal quartz. The several inclusions of biotite gneiss that occur within the Barley Mill Gneiss near the contact with the Wissahickon are interpreted to be xenoliths of country rock (Bc52-a). The small enclaves of amphibolite and hornblendite are probably cog-

nate inclusions related to the thicker amphibolite layers that occur within the gneiss (Bc53-k). Thus the composition and textures suggest the Barley Mill Gneiss is a pluton rather than a sedimentary melange.

Boundaries. The Barley Mill Gneiss is mapped as a linear pluton that was folded after intrusion into the Faulkland Gneiss and the Wissahickon Formation.

Type Section. The rocks at Tatnall School are designated as the type section for the Barley Mill Gneiss (Bc44-c and Bc44-f).

Lithology. The Barley Mill Gneiss is composed of felsic gneiss with or without mafic enclaves and amphibolite. The felsic gneiss has the composition of a tonalite, trondhjemite, or granodiorite (Streckeisen, 1976). The enclaves are either amphibolite or hornblende that may or may not have reaction rims. The proportion of amphibolite to felsic gneiss varies between rocks that are over 50 percent amphibolite and rocks that are 100 percent felsic gneiss.

At Wooddale, the rare contact between the Barley Mill Gneiss and the Wissahickon Formation is exposed (Bc52-a). At the contact the grain size in both units has been reduced to produce thin mylonitic layers that trend N45°E and dip at 90°. Large xenoliths (5 to 10 ft in diameter) of garnet-rich, pelitic rock occur near the margin of the gneiss. The presence of the xenoliths indicates a pre-mylonite spatial association between the Barley Mill Gneiss and the Wissahickon Formation and is evidence for an intrusive contact between the two units.

Petrology. The tonalitic gneiss is composed of about 45 percent plagioclase, about 32 percent quartz, 13 percent hornblende, and 10 percent biotite. Granodiorite phases are characterized by the absence of hornblende and the presence of orthoclase. A granodioritic boulder exposed near Tatnall School contains 46 percent plagioclase, 38 percent quartz, 12 percent orthoclase, and 4 percent biotite. Accessory minerals in the felsic units are ilmenite, zircon and apatite. The amphibolite contains subequal amounts of plagioclase and hornblende with minor biotite, quartz, and iron-titanium oxides. Hornblende grains are pleochroic green to dark green. They are elongated parallel to the biotite laths, and together they define a weak foliation. Quartz grains display subgrain boundaries and undulatory extinction. Equant grains of plagioclase (An₃₀) are, in some samples, antiperthitic and twinned on the albite, pericline and Carlsbad laws. Hornblende in the ultramafic enclaves is similar to that in the amphibolite.

Thin sections from the mylonitic contact in Wooddale show the layers of Wissahickon Formation are composed of quartz recrystallized into a mosaic of very small grains, long thin streaks of biotite-sillimanite, and porphyroclasts of plagioclase and garnet. The tonalitic layer is even finer-grained with stringers of recrystallized quartz, small pale green grains of hornblende, and porphyroclasts of plagioclase.

Metamorphism. The absence of pyroxene from assemblages in the Barley Mill Gneiss indicates metamorphism in the amphibolite facies, therefore metamorphic grade is lower in the Barley Mill Gneiss than in the adjacent Brandywine Blue Gneiss and the Faulkland Gneiss.

Deformation. Strike of the foliations and the trend of the lineations as defined by the orientation of the mafic minerals are variable except near the borders of the pluton

where they parallel the country rock. Deformation is most intense near the borders of the pluton, diminishes away from the boundaries and is absent from a few rocks near the core. The mylonite present between the Barley Mill Gneiss and the Wissahickon metasediments indicate no sense of shear, thus there is no evidence to suggest which direction the rocks have moved.

Age. SHRIMP U-Pb zircon ages for the Barley Mill Gneiss are 470±9 Ma (John N. Aleinikoff, U. S. Geological Survey, personal communication, 2000). The zircons were recovered from a sample of tonalitic gneiss (Bc53-k) collected during construction of Stonewold, a development near the type section. The sample contained only one population of elongate, prismatic (igneous) zircons.

Montchanin Metagabbro (herein named)

Definition. The Montchanin Metagabbro is the new name given to a body of amphibolite that occur within the Wissahickon Formation west of the Brandywine Blue Gneiss (Plate 1). The pluton is exposed in five separate areas within the Wilmington North quadrangle.

Historical Background. The Montchanin Metagabbro was originally mapped by Ward (1959) as amphibolite A, and included in the body of Wilmington Complex amphibolites that he mapped west of the banded gneisses. He describes the outcrops along the Brandywine Creek as interbedded amphibolite and pelitic gneiss. Woodruff and Thompson (1975) mapped the unit as undifferentiated inter-layered hornblende-plagioclase gneiss, pyroxene plagioclase gneiss, amphibolite, and quartz-plagioclase gneiss.

Srogi (1988, 1991) and Wagner and Srogi (1987) mapped these rocks as outliers of mafic and felsic gneiss of the Wilmington Complex surrounded by rocks of the Wissahickon Formation. They found a complex distribution of units, with the Wilmington Complex generally occupying topographic highs and the Wissahickon Formation occupying the lower areas. This led them to suggest the contact is a thrust fault that is almost horizontal, although foliations in both the Wissahickon and the Wilmington Complex dip steeply to the northwest and are strongly discordant with the interpreted contact surface.

Boundaries. Montchanin Metagabbro includes all the coarse-grained amphibolite that occurs west of the Brandywine Blue Gneiss, from Thompson's Bridge Road to south of Kennett Pike. Along the Brandywine Creek the metagabbro structurally overlies the pelitic gneiss of the Wissahickon. There is no field evidence to indicate if the contact between the pelitic gneiss of the Wissahickon Formation and the metagabbro is thrust or intrusive. The map pattern suggests the metagabbro is folded with the axial plane striking N18°E. Small isolated pods of metagabbro lie northeast of the fold crest (Plate 1).

Type Section. The type section for the Montchanin metagabbro is in Brandywine Creek State Park on the hill northeast of the upper parking lot (Bd21-a).

Lithology. The rock is a medium- to coarse-grained black amphibolite that may be either massive or weakly foliated. Metamorphic minerals are dominantly hornblende and plagioclase; however, in some locations the primary igneous minerals, olivine, clinopyroxene, orthopyroxene, and calcic plagioclase may be present. Along the hillside west of

Rockland a small pod of ultramafic rock is exposed. Black amphibolite with megacrysts of green clinopyroxene and magnetite grains with halos of quartz and feldspar are common features of the rock.

Petrography. Plagioclase and hornblende are the dominant minerals with large poikiloblastic grains of clinopyroxene and orthopyroxene present in some samples. Textures are heteroblastic and subophitic with various sizes of plagioclase grains coexisting in what appears to be textural equilibrium. Twinning of plagioclase grains is complex on the albite and Carlsbad laws. Plagioclase composition is between An₆₈ and An₇₂. Other than the weak foliation, there is little evidence for strain. Pristine ophitic textures were identified in some samples from Brandywine Creek State Park (L. Srogi, personal communication, 2000).

Metamorphism. The presence of hornblende and clinopyroxene as the dominant mafic minerals indicates metamorphism in the upper amphibolite facies.

Deformation. Foliations in the metagabbro and the underlying pelitic gneiss are concordant, striking northeast and dipping steeply northwest.

Age. No age has been determined for the Montchanin Metagabbro. It is metamorphosed and deformed; therefore, we assume it was emplaced before the regional metamorphism.

Mill Creek Metagabbro (herein named)

Definition. The Mill Creek Metagabbro is the new name given to the black, massive amphibolite that occurs along Mill Creek near Delcastle, Delaware within the Kennett Square and Newark East quadrangles. In the field the rock appears to be similar to the Montchanin Metagabbro, but because of the geographic separation and different chemistry, it is defined as a separate unit. Four abandoned quarries in this unit attest to the excellent building stone qualities of this rock.

Historical Background. Bascom and Stose (1932) mapped a large area of undifferentiated gabbro in the northeastern Piedmont of Delaware. The Mill Creek Metagabbro, was a part of the area they defined as “gabbro.”

Woodruff and Thompson (1972) mapped a body of amphibolite within the Wissahickon Formation at the approximate location of the Mill Creek Metagabbro. They described the unit as a hornblende-oligoclase to andesine gneiss and schist. Thompson’s 1981 map, portrayed in Howard (1986), shows the amphibolite as a klippe outboard and west of the Wilmington Complex. We have expanded the area originally mapped as a klippe and mapped it as a folded pluton that intrudes the Faulkland volcanic rocks.

Boundaries. The Mill Creek Metagabbro is surrounded on three sides by the Wissahickon Formation. The southwestern boundary is with the Faulkland Gneiss. The contacts with the Wissahickon Formation and the Faulkland Gneiss are never exposed. To the Southwest, the Mill Creek is truncated by a normal fault (Plate 1). Other than the quarry outcrops, the unit has been mapped on the basis of float.

Type Section. The Mill Creek Metagabbro is defined as a lithodemic unit within the Wilmington Complex. The quarries at the intersection of Mill Creek Road and Stoney Batter Road are designated as the type locality (Bb55-b, Cb15-a, and Cb15-b).

Lithology. In the field the amphibolite is black and coarse-grained. Elongated hornblende grains define a weak lineation. Grain size is variable with grains up to one half inch in diameter. During construction of the development of Thomas Pointe, a gabbroic pegmatite was observed. It is no longer exposed.

Petrography. The minerals in the metagabbro are about 60 percent hornblende, and about 40 percent plagioclase (An₆₂), with rare iron-titanium oxides. The hornblende grains are pleochroic in shades of green and are slightly elongated. The grains are hypidiomorphic and have no inclusions. Plagioclase is twinned on the albite and Carlsbad laws, and strain is recorded by deformation twinning.

Metamorphism. No pyroxenes were identified in the amphibolites of the Mill Creek Metagabbro, suggesting it is metamorphosed to the amphibolite facies. This is a lower grade than the Brandywine Blue Gneiss and the Montchanin Metagabbro but equivalent in grade to the adjacent Wissahickon Formation.

Deformation. The hornblende grains are aligned to produce a weak lineation that trends between N45°E and N10°E with a steep dip.

Age. No ages have been determined for the Mill Creek Metagabbro. Because it is metamorphosed and deformed we suggest it was emplaced before the high temperature regional metamorphic event.

Rockford Park Gneiss (herein named)

Definition. The Rockford Park Gneiss is composed of mafic and felsic gneiss interlayered on a scale of >6 in. The layers are laterally continuous and normally boudinaged. This unit is enclosed within the Brandywine Blue Gneiss, and both units are at lower granulite facies of metamorphism. The mafic layers have the composition of basalt, whereas the felsic layers are low-K, quartz-rich rocks that are compositionally equivalent to trondhjemite (Streckeisen, 1976). The Rockford Park Gneiss occurs within the Wilmington North quadrangle.

Historical Background. In Ward’s (1959) study, the Wilmington Complex banded gneiss included both the interlayered mafic and felsic gneiss, now the Rockford Park Gneiss, and the lineated felsic unit, now the Brandywine Blue Gneiss of this report. Ours is the first study to identify and map these two lithodemes within a redefined Wilmington Complex.

Boundaries. The bodies of Rockford Park Gneiss are surrounded by the Brandywine Blue Gneiss; however, penetrative deformation and granulite facies metamorphism have obscured the contact relationships.

Type Section. The Rockford Park Gneiss is defined as a lithodemic unit within the Wilmington Complex. The outcrops in Rockford Park in the city of Wilmington have been selected as the type locality (Bd41-b).

Lithologies. The mafic and felsic layers within the Rockford Park Gneiss have sharp boundaries with no grain size reduction or partial melting along the contact. The mafic layer is fine-grained, and commonly shows boudinage. Where the mafic boudins have separated, coarse-grained felsic gneiss fills the gap between the boudins. This coarse-grained material may have originated as a partial melt of the felsic layer, as an intrusion of somewhat younger

magma, or by an intrusion of primary age magma. Granitic pegmatites occur in thin layers that have been flattened and extended parallel to the mafic-felsic layering.

Petrography. The minerals in the felsic layer are >90 percent quartz and plagioclase (An₃₀ - An₅₀) and <10 percent orthopyroxene with/without clinopyroxene. Accessories are magnetite, apatite, and zircon. Grain boundaries are typically sutured, and strain is recorded by deformation twinning in plagioclase and undulatory extinction in quartz. Orthopyroxene is weakly pleochroic from pale pink to colorless. Minerals in the finer-grained (0.1-0.3 mm) mafic layer are plagioclase (An₃₃-An₆₄), orthopyroxene, clinopyroxene, and hornblende with minor quartz and biotite. Apatite and magnetite are the only accessories. Texture is granoblastic polygonal, plagioclase is complexly twinned, clinopyroxene is pleochroic pale pink to light green, and hornblende is pleochroic in shades of green and brown.

Metamorphism. The Rockford Park Gneiss is metamorphosed to granulite facies. The absence of pelitic assemblages in this unit precludes estimates of peak metamorphic temperature or pressure; however, they are most likely equivalent to those in the surrounding Brandywine Blue Gneiss where peak metamorphic conditions are estimated to be 800°±50°C and 6±1 kbar. (Wagner and Srogi, 1987; Srogi, 1988; Srogi et al., 1993; and L. Srogi, personal communication, 2000). Metamorphism within this unit decreases gradually from lower granulite facies in Delaware to amphibolite facies in Pennsylvania.

Deformation. Intense deformation within the Rockford Park Gneiss in Delaware has destroyed original textures and transposed all units; however, deformation diminishes in the Rockford Park Gneiss identified to the north in Pennsylvania. The large pod of Rockford Park Gneiss straddling the Delaware-Pennsylvania border (Plate 1) is much less deformed than the rocks to the south; for example, the mafic layers do not show boudinage, and folds are preserved. In most cases the layering in the Rockford Park Gneiss is parallel to the regional strike which trends approximately N40°E.

Geochemistry. The mafic layers in the Rockford Park Gneiss have distinctive trace element signatures that are similar to modern boninites. Boninites are unusual rocks erupted following the initiation of subduction that have been identified in the forearc regions of active arcs in the western Pacific (Plank et al., in press). The presence of boninitic rocks constrains the original environment of the Rockford Park Gneiss to the forearc region of a volcanic arc. Rocks of boninitic affinity have also been identified in Paleozoic rocks in the northern Appalachians where they have also been assigned to a subduction setting (Coish, 1989; Kim and Jacobi, 1996).

Age. U-Pb isotopic ages from igneous zircons in a felsic layer from the type section (Bd41-b) in Rockford Park are reported as 476±4 Ma, whereas metamorphic zircons in the same sample recorded an age of 432±6 Ma (John N. Aleinikoff, U. S. Geological Survey, personal communication, 2000). An age of 432±6 Ma is interpreted as the time of granulite-facies metamorphism.

Brandywine Blue Gneiss (herein named)

Definition. The Brandywine Blue Gneiss is the new name given to the granulite-facies felsic gneisses in the

Wilmington Complex. Informally called the “blue rocks,” this unit is a medium- to coarse-grained, lined (pin-striped), two-pyroxene gneiss with variable quartz content and thin, discontinuous mafic layers, pods, and schlieren. The pinstriping and the massive nature of the rock suggest the rock is intrusive; however, deformation and recrystallization have obscured original igneous features.

The unit appears on the Wilmington North, Wilmington South, and Marcus Hook quadrangles where it underlies the city of Wilmington and its northeastern suburbs.

The bright blue to blue-gray color of the gneiss when freshly quarried led 19th century stone cutters and local geologists to call this rock the Brandywine blue granite, the “blue rock of the Delaware Quarries” (Booth, 1841, p. 27), or the “blue granite of the Delaware quarries” (Chester, 1890, p. 8). To retain the local usage and priority of previous names, we have named this lithodeme the Brandywine Blue Gneiss.

Historical Background. The Brandywine Blue Gneiss and the Rockford Park Gneiss were mapped as one unit by Bascom and Miller (1920), Bascom and Stose (1932), Ward (1959), and Woodruff and Thompson (1975). Ward’s (1959) map labeled the pyroxene-bearing felsic and mafic gneisses the “banded gneiss.” He used this vague term to avoid using gabbro, metagabbro, or migmatite, which he thought might have strong genetic implications.

Woodruff and Thompson (1975) separated units of the Wilmington Complex by mineralogy and rock type without naming them. They described the granulite facies gneisses as metaigneous and metasedimentary, hypersthene-quartz-andesine gneisses with minor biotite and magnetite. Mineral lineations locally suggest orthogneissic texture. The amphibolite facies gneisses were described as interlayered metaigneous and metasedimentary hornblende-plagioclase gneisses.

More recent partial maps of Ward’s banded gneiss include those of Mark (1977), Thompson (1981, map in Howard, 1986), Srogi (1982, 1988), and Wagner and Srogi (1987).

Boundaries. The Brandywine Blue Gneiss comprises the bedrock east of Route 202 and under the City of Wilmington and a small area in southeastern Pennsylvania. Its northern boundary, north of the map area (Plate 1), is in contact with large masses of serpentinite bordering the Avondale anticline. Along its western margin the gneiss is in contact with the Wissahickon Formation and the Faulkland Gneiss. This contact parallels Rt. 141, but it is not exposed. The eastern margin is in contact with the Wissahickon Formation and the Arden Plutonic Suite. To the south along the fall zone, sediments of the Coastal Plain overlap the gneiss. Also to the south, the Brandywine Blue Gneiss is intruded by the Bringhurst Gabbro. Cores drilled for the construction of the Rt. 141 bridge over the Christina River in Newport, Delaware, indicate the Brandywine Blue Gneiss lies under the Coastal Plain sediments at depths of 50 to 100 ft (Cc34-41) (Schenck and Plank, 1995).

Type Section. The Brandywine Blue Gneiss is defined as a lithodemic unit within the Wilmington Complex. The large quarries along the east side of the Brandywine Creek adjacent to the Northern Delaware Greenway provide excellent exposures of the Brandywine Blue Gneiss (Bd42-e).

Lithology. Monotonous coarse-grained felsic gneisses with thin, minor discontinuous layers and lenses of mafic minerals are characteristic of the Brandywine Blue Gneiss. Locally, the gneisses may be melanocratic or very leucocratic. On a fresh surface the rocks appear blue-gray and massive, whereas on the weathered surface the mafic minerals and elongated quartz megacrysts form a pervasive lineation that appears as pinstriping. On the basis of the massive appearance in the field, possible relict flow textures reflected by the mineral lineations, and contamination along the borders of the unit, we postulate the unit is a felsic pluton.

Included within the Brandywine Blue Gneiss are small pods of garnet-bearing aluminous gneiss that may be clasts, xenoliths of country rock, or weathering horizons (Srogi, 1988; Srogi and Lutz 1997).

Petrology. Felsic gneisses are composed of >60 percent quartz and plagioclase with or without orthopyroxene, clinopyroxene, and brown-green hornblende. Accessory minerals are magnetite, zircon, and apatite. Alkali feldspar and garnet are absent. Biotite is present only as a secondary alteration product of orthopyroxene and is most abundant near contacts with the other units and in shear zones. Plagioclase compositions range from andesine to labradorite. Quartz occurs as large megacrysts as well as smaller grains in the matrix. Orthopyroxene is pleochroic pale pink to light green. Grain boundaries are typically sutured, and the texture is inequigranular interlobate to amoeboid.

The minerals in the fine-grained mafic gneisses are plagioclase, hornblende, clinopyroxene and/or orthopyroxene, and magnetite. The texture of mafic gneisses is commonly granoblastic polygonal.

In some felsic gneisses, quartz grains with undulatory extinction, plagioclase grains with deformation twinning, and granulation around both quartz and plagioclase grains indicate strain or cataclastic deformation. Microscale deformation is minor in the mafic layers. Modes and a description of the microtextures can be found in Ward (1959).

Metamorphism. The Brandywine Blue Gneiss was metamorphosed to granulite facies. Peak metamorphic conditions of $800 \pm 50^\circ\text{C}$ and pressures of 6 ± 1 kbar were estimated using various geothermometers and geobarometers (Srogi, 1988; Wagner and Srogi, 1987, L. Srogi, personal communication, 2000). Srogi et al. (1993) describe the prograde and retrograde metamorphic reaction history in the garnet-bearing gneisses in the Brandywine Blue Gneiss. Their results infer that peak metamorphic conditions were associated with magmatic heating.

With the exception of strongly deformed rocks near the contact with the Wissahickon Formation, the gneisses show little evidence for retrograde metamorphism.

Deformation. Boudinage fabrics in the Brandywine Blue Gneiss suggest a high degree of deformation. Mineral lineations are due to a preferred orientation of hornblende, pyroxene, or quartz and can best be recognized on weathered surfaces. The lineations trend northwest while the strike of minor foliations and layering vary between $N20^\circ\text{W}$ and $N55^\circ\text{E}$. Dips are generally greater than 45° . Small scale folding is rarely observed in the felsic gneiss.

Age. Grauert and Wagner (1975) obtained a U-Pb zircon age for the Brandywine Blue Gneiss of 441 Ma and interpreted it to be the age of the granulite facies metamorphism. New SHRIMP U-Pb isotopic ages from igneous zircons in the felsic gneiss (Bd42-e) are reported as 476 ± 6 Ma (John N. Aleinikoff, U. S. Geological Survey, personal communication, 2000).

Arden Plutonic Supersuite (herein redefined)

Definition. The Arden Plutonic Supersuite includes orthopyroxene-bearing gabbro, diorite, quartz diorite, quartz monzonite, granodiorite, granite, and tonalite that intrude the Brandywine Blue Gneiss and Wissahickon Formation. On the basis of field, petrographic, and geochemical evidence, we group the igneous rocks into two suites, the Ardentown Granitic Suite (formerly the Arden Granite of Ward, 1959), and the Perkins Run Gabbronorite Suite, as well as an additional biotite tonalite lithodeme. The Arden Supersuite is located within the Marcus Hook quadrangle beneath the northeastern suburbs of Wilmington, Delaware, and the Bethel, Lower Chichester, and Upper Chichester townships, Pennsylvania.

Historical Background. The Arden Supersuite has been mapped and interpreted in several different ways in previous work. Bascom et al. (1909), Bascom and Miller (1920), and Bascom and Stose (1932) used the term “gabbros” to include a variety of igneous and metamorphic rocks now mapped as Arden Supersuite and Brandywine Blue Gneiss. The rocks were probably called “gabbros” because of their dark gray color on fresh surfaces, and they were interpreted to be younger than the Wissahickon Formation. Ward (1959) was the first to distinguish intrusive igneous rocks from the more deformed and recrystallized gneisses within the Wilmington Complex. He named the largest pluton the Arden Granite, in reference to the historic single-tax community of craftspeople and artists established in 1900 (Wiencek, 1992). Ward (1959) described the unusual mineralogy of the Arden Granite, which includes pyroxenes and perthitic feldspars, but did not recognize the presence of gabbroic rocks within the pluton. On the basis of a model popular at the time, he considered the Arden Granite to have formed by metasomatism. Thompson (1975) was the first to recognize the Arden as a composite pluton with a variety of igneous lithologies that crystallized from magma, rather than formed by metasomatism. He identified the igneous rocks as members of a comagmatic anorthosite suite comprising anorthosite, gabbroic anorthosite, opdalite, and charnockite, that intruded both “hypersthene-quartz-plagioclase and calc-silicate gneisses” of the Wilmington Complex. Mark (1977) re-mapped and described the Arden Pluton in Pennsylvania using Thompson’s nomenclature for the igneous rocks and the terminology of Winkler (1976) for foliated or recrystallized metamorphic rocks. The rock units of Mark (1977) and Woodruff and Thompson (1975) do not match up along the Delaware-Pennsylvania border, the major difference being in the characterization of rocks as “anorthosite” (igneous and part of the Arden Pluton) or “granolite” (metamorphic Wilmington Complex gneiss). The geologic map of Pennsylvania (Berg, 1980) also shows the Arden Pluton to be composed of anorthosite.

Subsequent work (Srogi, 1988; Dirska, 1990; Srogi and Lutz, 1997) provides a more detailed and accurate characterization of the Arden Pluton, herein designated the Arden Plutonic Supersuite. Most importantly, none of the igneous rocks is anorthosite; the rocks contain much less than 90 modal percent plagioclase. Further, the silicic igneous rocks (“opdalite and charnockite”) are mineralogically and chemically unlike those associated with anorthosite massifs (Wagner and Srogi, 1987, pp. 119-121). In brief, igneous rocks associated with anorthosite massifs are typically alkaline and contain a higher ratio of alkali feldspar to plagioclase compared with the silicic rocks of the Arden Supersuite, which are calc-alkaline (Wagner and Srogi, 1987). The misidentification may result from the resemblance in hand specimen of many Arden Supersuite rocks to Adirondack-type anorthosites. A comprehensive study (Srogi, 1988) recognized two principal igneous units in the Arden Supersuite: a comagmatic suite ranging from quartz norite to charnockite, herein called the Ardentown Granitic Suite, and gabbroic rocks herein called the Perkins Run Gabbroic Suite. Srogi (1988) summarized the complex field relationships between the two units and tentatively concluded that the granitic rocks intruded the gabbroic rocks. Additional field and petrographic work has revealed extensive evidence for commingling and hybridization (Srogi and Lutz, 1997; Miller and Srogi, 1999). This has led to the current interpretation that the magmas that formed the Ardentown and Perkins Run suites were contemporaneous.

Boundaries. The Arden Supersuite extends from the Delaware River just east of Bellefonte, Delaware, to Bethel, Lower Chichester, and Upper Chichester townships in Pennsylvania. The pluton boundaries on the present map are only slightly different from previous maps (Woodruff and Thompson, 1975; Mark, 1977; Crawford and Crawford, 1980; Berg, 1980; Srogi, 1988; Srogi and Lutz, 1997). The major change is the recognition that the Wissahickon Formation occurs within and along the northeast side of the pluton. Thus, we conclude that the Arden Supersuite intrudes the Wissahickon Formation as well as the Brandywine Blue Gneiss. In addition, new float and outcrops revealed by development provide evidence that the pluton extends north of Rt. 322, but does not extend west of Rt. 261. The western margin of the pluton is constrained by float and outcrop in several streams that run almost perpendicular to the contact, whereas the location of the eastern margin of the pluton is not as well constrained. The southern margin of the Arden Supersuite is covered by Coastal Plain sediments and alluvium of the Delaware River.

Deformation. In the field, most Arden Supersuite rocks have igneous textures without preferred orientation, but many have measurable foliation or lineation. Foliation or lineation defined by alignments of relatively unstrained, tabular feldspar grains or phenocrysts, elongate mafic minerals, or mafic enclaves may meet the criteria for an origin by magmatic flow (Paterson et al., 1989; Vernon et al., 1988). Locally, the rocks in the Arden Supersuite display features that suggest subsolidus ductile deformation, such as grain size reduction, ovoid shapes of feldspar, pyroxene, or hornblende, or the development of tails on phenocrysts.

All of the igneous rocks contain microstructural evidence for intracrystalline strain, ranging from slight to

intense. Deformation features observable in thin section include bent twins and deformation twinning in plagioclase; bent exsolution lamellae in pyroxenes, sutured grain boundaries in feldspars and quartz; grain size reduction around the margins of pyroxenes, feldspars, and quartz; and kink band development and microfractures in pyroxenes, feldspars, and biotite. The most deformed rocks resemble protomylonites in thin section; however, very few of the igneous rocks exhibit significant recovery or recrystallization. For example, a quartz norite from the Ardentown Granitic Suite that shows intense ductile deformation still has magmatic oscillatory zoning in plagioclase phenocrysts and has the same plagioclase and pyroxene compositions as relatively undeformed rocks.

It is difficult to assess the significance of structures within the Arden Supersuite because outcrop is limited. Given the small amount of available data, structures plotted on the geologic map are not separated according to origin by magmatic or subsolidus processes. Near the margins of the pluton, foliation typically has a margin-parallel strike and steep to vertical dip. Outcrops in the pluton interior have fabrics that dip moderately to the northwest. At the present time we are still investigating the extent to which the fabrics in the Arden Supersuite rocks reflect stress regimes during pluton emplacement, syntectonic crystallization (e.g., Pavlis, 1996), or post-crystallization regional deformation.

Ardentown Granitic Suite (herein named)

Type Section. The type section for the Ardentown Granitic Suite is the South Branch of Naaman Creek, from Harvey Mill Park just west of Rt. 3 and Ardentown, Delaware, to the confluence with Naaman Creek (Be21-e, Be22-e, Be22-k, Be23-f, and Be23-g) just west of the intersection of Rts. 491 and 92 near Knollwood (formerly Worthland). The Ardentown type section includes the contact between the Ardentown Suite and the Brandywine Blue Gneiss along the western margin of the pluton.

Lithology. The Ardentown Granitic Suite is characterized by medium to coarse grain size, the presence of quartz, and porphyritic texture with phenocrysts of plagioclase, K-feldspar, or both up to two inches in long dimension. On fresh surfaces, most rocks are a uniform dark gray color, and the feldspar phenocrysts have a brilliant, glassy luster. The texture and mineral content are easily recognized on weathered surfaces where feldspars are light gray, pyroxenes and biotite appear black or brown, and quartz commonly stands out as less-weathered blebs. Phenocrysts may display Carlsbad twinning in K-feldspar and concentric zoning in plagioclase. Mafic enclaves are common in the Ardentown Suite and are locally abundant in proximity to the gabbroic rocks.

Lithodemes within the Ardentown Granitic Suite include quartz norite, quartz monzonite, opdalite, and charnockite, using nomenclature for rocks containing orthopyroxene and clinopyroxene (Streckeisen, 1976). Whereas the Ardentown Suite includes rocks other than true granite (or charnockite), the term “granitic” was chosen to convey the overall silicic character of the rocks and because the rocks probably crystallized from a granitic magma (Srogi, 1988; Srogi and Lutz, 1997). Quartz norite and monzonite have the highest color index in the Ardentown

Suite and contain up to 20 modal percent pyroxenes and a few percent biotite. Even the most mafic quartz norites contain around 10 modal percent quartz and K-feldspar. Quartz norite, monzonite, and opdalite are typically the most porphyritic rocks, containing 10-15 modal percent feldspar phenocrysts. Charnockite is the most leucocratic lithodeme in the suite and may be light gray or buff to orange on fresh surfaces. More extensive descriptions, photographs, and analyses of Ardentown Suite rocks and minerals can be found in Srogi and Lutz (1997) and Srogi (1988).

Petrography. The members of the Ardentown Granitic Suite share a common mineralogy comprising plagioclase, orthopyroxene, clinopyroxene, K-feldspar, quartz, and biotite (Srogi, 1988; Srogi and Lutz, 1997). Euhedral to subhedral feldspar phenocrysts are set in a matrix with hypidiomorphic-granular to allotriomorphic-granular texture. The concentric zoning observed in plagioclase phenocrysts in hand specimen is produced by variations in the abundance of orthoclase blebs within the plagioclase host, forming alternating antiperthitic and non-antiperthitic zones. The host plagioclase is typically not zoned in Na and Ca content and has a composition in the range An_{33} to An_{37} (Srogi and Lutz, 1997). Most K-feldspar is microperthitic to cryptoperthitic orthoclase; low microcline has been identified only in two samples that show greater subsolidus recrystallization (Srogi and Lutz, 1997, and references therein). Myrmekite is common along grain boundaries of K-feldspar. Some feldspars have chlorite-filled microfractures, but are not otherwise altered by fluids. Pyroxenes occur as subhedral to euhedral grains or in glomeroporphyritic clusters. Orthopyroxene, with pale pink-green pleochroic colors, is typically more abundant than the pale green clinopyroxene. Both pyroxenes commonly have fine-scale exsolution lamellae (of clinopyroxene in orthopyroxene and vice versa). Pyroxene compositions show slight iron enrichment from the most mafic to the most silicic rocks in the Ardentown Suite (Srogi and Lutz, 1997). In all rocks, biotite is a minor constituent (from less than 1 to 5 modal percent) and is pleochroic in shades of pale yellow to deep reddish-brown. Clustered flakes with abundant apatite and zircon inclusions may be of magmatic origin, but most grains appear to be replacing pyroxene by reactions with fluids. Hornblende is very rare and is associated with mafic enclaves. Accessory magnetite, ilmenite, zircon, apatite, and monazite are associated with pyroxenes and plagioclase, and are rarely found in the most silicic rocks.

Age. There are two different zircon U-Pb isotopic ages for the Ardentown Granitic Suite. A slightly discordant U-Pb age of 422 ± 6.5 Ma was obtained by Secondary Ion Mass spectrometers (SIMS) analysis of zircons from one sample of quartz norite (Be32-b; Bosbyshell et al., 1998). A more recent determination of 434 ± 4 Ma was obtained by SHRIMP analysis of zircons from a different sample of quartz norite (sample Be23-f; John N. Aleinikoff, U. S. Geological Survey, personal communication, 2000). Both ages support field evidence that the Arden Pluton crosscuts and is therefore younger than the Brandywine Blue Gneiss. We prefer the age of 434 ± 4 Ma as the best estimate for the time of magmatic crystallization because of the discordance in the SIMS results and the intense subsolidus deformation observed in that sample (Be32-b). While it is possible that

the Ardentown Granitic Suite contains igneous rocks of different ages, Srogi and Lutz (1997) presented geochemical evidence for the derivation of the Ardentown Suite from a common granitic parent magma. A previous study by Foland and Muessig (1978) determined a Rb-Sr isochron age of 502 ± 20 Ma, and an initial $^{87}\text{Sr}/^{86}\text{Sr}$ isotopic ratio of about 0.7065, for rocks of the Ardentown Granitic Suite. Given the new, younger age of the pluton, the significance of these analyses is still being investigated.

Perkins Run Gabbronorite Suite (herein named)

Type Section. The type section for the Perkins Run Gabbronorite Suite is located in the southwestern part of the pluton. It extends along Perkins Run and its unnamed western tributary, from Business Rt. 13 in the south to I-95 in the north (Be32-g, Be32-h, Be32-m, Be32-n, Be32-x). This type section was chosen to encompass most of the textural and mineralogical varieties of gabbroic rocks within the pluton.

Lithology. The gabbronorites are distinguished in the field from the Ardentown Granitic Suite by the greater abundance of mafic minerals (30-50 modal percent), the presence of hornblende, and the absence of quartz and K-feldspar. In addition, the texture is commonly subophitic in hand specimen, or may show a weakly- to strongly-developed lineation or foliation. Grain sizes are typically around 0.2-0.4 in, but locally may be much finer or coarser. Fresh rock surfaces are dark gray to black in color. Textures and mineral content are most easily observed on weathered surfaces where plagioclase is light gray, orthopyroxene is brown, clinopyroxene is dark green to black with a duller luster, and hornblende appears very black and lustrous. Olivine is green and glassy where fresh but weathers to form orange-brown, iron hydroxide-coated pits.

There is great textural variety in the Perkins Run Suite, depending on the grain size and extent of mineral preferred orientation. Unfoliated gabbronorite typically has a subophitic texture. The lineation or foliation is defined by alignments of elongate grains or chains of mafic minerals, and plagioclase phenocrysts (if present). Gabbronorite with the strongest fabric also contains abundant hornblende. In previous work, Srogi (1988 and field notes) referred to unfoliated gabbronorites as "pristine gabbros," and the foliated gabbronorites as "hornblende meta-gabbros" (also "amphibolitized gabbros" or "blotchy gabbros" in field notes).

There is considerable field evidence for mutually intrusive relationships within the Arden Supersuite. First, there are multiple phases of gabbronorite that can be seen to intrude each other along the Perkins Run type section and other places, such as in Naaman Creek near I-95. Secondly, there is evidence for commingling of contemporaneous granitic (Ardentown Suite) and gabbroic (Perkins Run Suite) magmas (Miller and Srogi, 1999). Evidence that can be observed along the Ardentown Granitic Suite type section includes contacts and mingling relationships between gabbronorites and granitic rocks; an increased abundance of mafic enclaves in Ardentown Suite rocks near gabbronorite; mafic enclaves with lobate, "pillow-like" shapes and crenulate margins typical of mafic magmas chilled within a granitic host magma (see examples cited in Didier and Barbarin, 1991); and rocks that may be "hybrids" or mixtures between gabbroic and granitic magmas (Miller and

Srogi, 1999). Further, gabbronorite along the Perkins Run Suite type section is more fine-grained and contains abundant hornblende (\pm biotite) in proximity to the Ardentown Granitic Suite, features observed in other plutons with commingled magmas (see examples cited in Didier and Barbarin, 1991, Zorpi et al., 1989).

Petrography. All but a few of the rocks fulfill the International Union of Geological Sciences (IUGS) definition of gabbronorite (Streckeisen, 1976), with labradorite plagioclase (An_{50-70}) comprising 50-60 percent of the mode, and both orthopyroxene and clinopyroxene present in subequal proportions, typically comprising between 20 and 30 percent of the mode. A few samples that contain andesine (An_{30-50}) should properly be termed diorites (Streckeisen, 1976) but belong with the Perkins Run Suite. Plagioclase compositions were estimated from optical properties (Srogi, 1988). In thin section, unfoliated gabbronorite has subophitic, hypidiomorphic-granular, or fine-grained intergranular texture. Foliated gabbronorite has hypidiomorphic-granular or intergranular texture, with alignments of tabular plagioclase, elongate mafic minerals, or chains of granular mafic minerals.

Plagioclase occurs as subhedral laths and as more anhedral granular grains. Plagioclase phenocrysts up to about an inch in long dimension occur in some rocks and may contain inclusions of pyroxene, hornblende, and/or biotite. Olivine is present only in some of the subophitic gabbronorites, where it makes up from 1 to 10 percent of the mode. Olivine is typically subhedral to anhedral and rimmed by orthopyroxene and green hornblende with spinel symplectites. Orthopyroxene and clinopyroxene occur as subhedral to anhedral grains with fine-scale exsolution lamellae (clinopyroxene in orthopyroxene and vice versa). Hornblende is ubiquitous, making up about 10 to 40 modal percent, and is pleochroic in shades of brown and green. Hornblende typically occurs as subhedral to anhedral grains, separately or in clusters with pyroxenes. In gabbronorites with subophitic texture, brown hornblende also occurs as rims on and inclusions within pyroxenes. In all gabbronorites, biotite is a minor constituent if present. Opaque minerals (mostly Fe-Ti oxides) range from 1-3 modal percent in subophitic gabbronorites to 5-10 modal percent in other textural varieties of gabbronorite. Other accessory minerals observed include apatite, sulfides, rutile (in one subophitic gabbronorite), and quartz (in one diorite). A few unfoliated gabbronorites from the central, northern, and eastern portions of the pluton contain significant amounts of secondary minerals including actinolitic hornblende, blue-green hornblende, talc, scapolite, and titanite, possibly indicating more extensive interactions with subsolidus fluids in those areas.

The Perkins Run Gabbronorite Suite denotes a group of temporally and spatially related rocks that formed by crystallization of one or more mantle-derived basaltic magmas. The mineralogy and rock compositions are consistent with magmas of tholeiitic basalt composition (Srogi, 1988). Field evidence for commingling with the Ardentown Granitic Suite suggests that at least some of the Perkins Run rocks are the same age as the Ardentown.

Biotite Tonalite

Type Section. The biotite tonalite occurs only as boulders of float in three locations within the northern part of the

Arden Pluton, in Bethel Township, Pa. A locality along Naaman Creek (Ae52-g) is chosen for the type section because the sample from this locality was analyzed chemically and petrographically.

Lithology. The biotite tonalite occurs as rounded boulders with light gray to buff colors on fresh and weathered surfaces. The tonalite is leucocratic and contains 15-25 percent mafic minerals. The biotite tonalite can be distinguished from the Ardentown Granitic Suite in hand specimen by a finer-grained equigranular texture and the scarcity or absence of K-feldspar. Chemically, the biotite tonalite differs markedly from Ardentown Suite rocks of comparable silica content (70 percent SiO_2 by weight) in having significantly lower K_2O (0.69 vs. about 3.5 weight percent), as well as some differences in trace element abundances (Srogi, 1988).

Petrography. Only one sample of tonalite has been analyzed petrographically. This sample has hypidiomorphic-granular texture and is primarily composed of subhedral plagioclase and about 20-25 modal percent quartz. Strongly pink-green pleochroic orthopyroxene and pale-to-dark brown pleochroic biotite are present in roughly subequal proportions, making up around 15-20 percent of the mode. The minerals show intracrystalline strain, similar to that described for the Ardentown Granitic Suite, with noticeable development of subgrains in quartz.

The biotite tonalite resembles the leucocratic portions of migmatitic Wissahickon Formation in thin section, and it occurs in the northern portion of the pluton where a megaxenolith of Wissahickon Formation is found. Thus, the biotite tonalite may have originated by partial melting of Wissahickon Formation gneisses such as those in Marcus Hook and Trainer, or perhaps of the Brandywine Blue Gneiss. Mafic enclaves found in some samples of tonalite could be unmelted restite from the source rock, or could have been derived from the Perkins Run Gabbronorite.

Bringhurst Gabbro

Definition. Olivine-bearing gabbros and gabbronorites of the Bringhurst Pluton intrude the Brandywine Blue Gneiss in the area of Bringhurst Woods Park. The gabbros are very coarse grained with ophitic to subophitic textures that show little evidence for metamorphism or deformation. The pluton is located in the Wilmington North quadrangle northeast of the City of Wilmington.

Historical Background. Ward (1959) was the first to identify a small, undeformed gabbroic pluton in the area of Bringhurst Woods Park northeast of the City of Wilmington. Woodruff and Thompson (1975) recognized that the pluton covered a much larger area and revised Ward's boundaries on their 1975 map. They describe the rock as a norite and noritic anorthosite containing andesine, hypersthene, and clinopyroxene (Wagner et al., 1987).

Boundaries. The pluton intruded the Brandywine Blue Gneiss and is surrounded by the gneiss on all sides except along its southern margin where it is overlain by sediments. In addition to field mapping, the extent of the gabbro was determined from a magnetic anomaly related to the gabbro (Fisher et al., 1979).

Type Section. The outcrops exposed along Shellpot Creek in Bringhurst Woods Park are designated as the type locality (Bd44-b).

Lithology. The gabbro of the Bringhurst pluton ranges in composition from gabbro to gabbro-norite, troctolite, norite, and anorthositic norite. The rocks are very coarse-grained with subophitic textures; typical grain size averages about 0.5 inch in diameter. A pegmatitic phase of the gabbro in which plagioclase laths measure up to 1 ft in length is exposed in Bringhurst Woods Park.

A contact between the Bringhurst Gabbro and the Brandywine Blue Gneiss is exposed along Shellpot Creek. The layering in the gneisses is disrupted, and some rocks appear migmatitic. The nature of the contact indicates that the gabbros were intrusive into the gneisses after they were deformed and metamorphosed. Mafic xenoliths, presumably derived from mafic units of Brandywine Blue Gneiss, are abundant in the gabbro. The absence of felsic xenoliths may be due to melting of the felsic gneiss in the hot gabbroic magma (Wagner et al. 1987).

Petrography. The primary minerals are plagioclase, olivine, clinopyroxene, and orthopyroxene. Olivine is less common than the other minerals and is surrounded by double coronas, with an inner corona of orthopyroxene, commonly as symplectites with spinel, and an outer corona of paragonitic hornblende, also as symplectites with spinel. Clinopyroxene is usually exsolved and replaced in patches by hornblende as well as locally being surrounded by coronas of hornblende. The plagioclase in most gabbros ranges from An₅₅ to An₈₀. The primary orthopyroxene is usually bronzite or hypersthene. Cumulate textures are commonly seen in thin section (Wagner et al. 1987).

Geochemistry. REE patterns and trace element abundances in gabbros from the Bringhurst pluton suggest derivation from mantle sources similar to those for E-MORB. Field evidence precludes an origin in a mid-ocean ridge environment; therefore, we conclude that the gabbro was probably associated with late rifting and extension within a magmatic arc (Plank et al., in press).

Age. There are no ages available for the Bringhurst; however, because it is undeformed, we conclude that it is as young or younger than the Arden which is also undeformed and has an igneous age of 434±4 Ma (John N. Aleinikoff, U. S. Geological Survey, personal communication, 2000).

Iron Hill Gabbro

Description. Iron Hill and Chestnut Hill in Delaware and Grays Hill in Maryland are outliers of the Piedmont, with Iron Hill rising 340 ft above sea level in the Atlantic Coastal Plain south of Newark. The bedrock that supports the hills is a mixture of gabbro and pyroxenite typically altered to uralite and serpentinite.

The hills are covered with yellow-brown rocks with a "honeycomb" texture. The cover rocks formed as weathering decomposed the gabbros and leached away much of its substance, leaving a layer of iron oxides mixed with ferruginous jasper called a gossan (Leavens, 1979). The jasper is cryptocrystalline and contains thin seams lined with drusy quartz. At various times between 1700 and 1891 the iron oxides, primarily limonite and hematite, were mined from both Iron and Chestnut hills. The Iron Hill Museum provides an interesting description of the early mining industry.

Iron Hill, Chestnut Hill, and Grays Hill are most likely part of a single pluton; however, contact relations are

unknown because the three hills are surrounded by sediments of the Atlantic Coastal Plain. The pluton is located in the Newark West and Newark East quadrangles.

Historical Background. Ward and Groot (1957) and Ward (1959) were the first to apply the name Iron Hill Gabbro to the rocks in the vicinity of Iron and Chestnut hills south of Newark, Delaware. On the basis of samples recovered from water wells, they postulated that the rocks in the three hills are similar but are surrounded by and separated from each other by what was then mapped as Port Deposit granodiorite.

They noted the uralitization of the primary pyroxenes to fibrous amphiboles and the alteration of olivine to masses of serpentinite and attributed the alterations to post-crystalline thermal or hydrothermal metamorphism at low-grade conditions.

Dirska (1990) compared the chemistry of the Iron Hill gabbros with the Bringhurst and Arden gabbros and concluded that they are not genetically related.

Boundaries. Iron Hill Gabbro is exposed south of Newark in three hills that protrude through sediments of the Atlantic Coastal Plain. The boundaries of the pluton on Plate 1 are slightly different from the previous map of Woodruff and Thompson (1972) as we show the area of gabbro beneath the coastal plain sediments. Modifications are based on recent fieldwork and well and test boring data.

Type Section. The Iron Hill Gabbro is the name proposed for the gabbroic rocks of Iron Hill and Chestnut Hill in Delaware and Grays Hill in Maryland. The boulders and outcrops along the banks of Christina Creek in Rittenhouse Park plus the small boulder field that occurs on the southwest side of the creek, northeast-facing slope, are designated as the type section (Da15-h). The Park is located 0.5-miles southwest of Route 896 off Chestnut Hill Road.

Lithology. Gabbros and olivine-pyroxenites exposed in construction sites and in areas where streams have cut through the gossan layer are dark gray, coarse-grained to very coarse-grained (0.25 to 0.5 inch grains) rocks with little evidence of deformation. On fresh surfaces the rock is dark colored, and the plagioclase has a pronounced schiller. Green olivine grains rimmed by pyroxene are visible on fresh surfaces. Weathered surfaces commonly show rusty pits recording the former presence of olivine grains. Outcrops of serpentinite, which are always deeply weathered, are dull-green and friable.

Petrology. The original minerals in the gabbros are orthopyroxene, clinopyroxene, and plagioclase. In most cases the pyroxenes are altered to pale blue-green uralite of probable actinolitic composition. Opaque minerals occur exclusively as inclusions in pyroxenes/uralites. The original minerals in the pyroxenites were orthopyroxene, clinopyroxene, and olivine with minor plagioclase. The pyroxenes are partially altered to uralite, and olivine occurs in various stages of alteration to serpentinite. Plagioclase, which is very calcic (An₆₅-An₉₀), ranges from 50 percent in the gabbros to 5 percent in the pyroxenites (Ward, 1959). Rare corona structures similar to those that occur in the Bringhurst Gabbro (Wagner et al., 1987) have been observed where olivine is in contact with plagioclase (Dirska, 1990).

Metamorphism and Deformation. Although at the surface the Iron Hill Gabbro has been extensively altered by

hydrothermal fluids, as evidenced by the uralitization of the pyroxenes and the serpentinization of the olivine, the gabbro under the altered layer is undeformed and unmetamorphosed, sometimes with original cumulate textures preserved (Dirska, 1990).

Age. No age has been determined for the Iron Hill gabbro; however, it is undeformed and unmetamorphosed suggesting that it may have intruded at approximately the same time as the gabbro in the undeformed and unmetamorphosed Arden Plutonic Supersuite and Bringhurst Gabbro.

Diabase Dike

Definition. Branca (1979) reported and mapped a small diabase dike exposed during the construction of Goldey Beacom College near Mermaid, Delaware. We have extended this dike from outcrop and float exposed during recent construction of a community called North Point along Stoney Batter Road. The diabase is located at the northern edge of the Newark East quadrangle. The diabase is probably Mesozoic in age.

Boundaries. The diabase is contained within the Wissahickon Formation. Branca (1979) reports chilled margins at the contacts with the country rock. We observed no contacts with the surrounding Wissahickon gneisses and mapped the extent of the diabase on the presence of float. The diabase is truncated by a fault on the northeast side and is extended to the southwest based on Branca's (1979) study. The diabase strikes N40°E, concordant with the strike of the surrounding Wissahickon gneisses.

Type Section. Boulders of the diabase are preserved opposite the tennis courts near the entrance to the greenway behind North Point and serve as the type section for this unit (Cb14-a).

Lithology. The diabase is composed of fine- to coarse-grained pyroxene and plagioclase. Branca (1979) reports subophitic textures with bladed pyroxenes enclosing thin laths of plagioclase. Branca also reports that the grain size is fine at the contact suggesting a chilled igneous contact.

Petrology. According to Branca (1979) the diabase contains plagioclase, hypersthene, augite, and hornblende. Magnetite, hematite, quartz, apatite, and biotite are accessories in trace amounts. Plagioclase is An₅₀₋₅₇, and most laths are twinned according to albite, Carlsbad, and pericline laws. Hypersthene occurs as subophitic laths and is pleochroic from pale pink to green. Augite is anhedral with pale green pleochroism. Hornblende is anhedral, partially surrounds the hypersthene, and is pleochroic in shades of green.

Metamorphism and Deformation. The diabase is undeformed and unmetamorphosed.

Age. The diabase is post-tectonic and is truncated by a brittle fault. Although we suggest a Mesozoic age, the macroscopic appearance of the diabase does not resemble the Triassic diabase dikes in Pennsylvania (R. C. Smith, Pennsylvania Geological Survey, personal communication, 2000).

GEOCHEMISTRY OF THE MAFIC ROCKS

Fieldwork in ancient, highly metamorphosed and deformed terrains is often difficult because many varieties of gneiss look alike. To make it even more difficult, the

metamorphosed and deformed rocks of the Delaware-Pennsylvania Piedmont occur in a densely populated area where exposures are restricted to streambeds, construction sites, and rock cores. We found that the geochemical characteristics of the mafic igneous rocks are useful in identifying rock units, and when combined with field identification provided a basis for grouping various rocks into mappable units.

Samples from 18 mafic rocks in the Wilmington Complex were analyzed for major and trace elements. In high grade metamorphic rocks the incompatible high field strength elements (HFSE) including the rare earth elements (REE) are considered to be immobile and most useful in correlating rock units. As expected, the trace elements provided a quantitative basis for grouping rocks into units that can be identified in the field. In addition, R. C. Smith and John H. Barnes of the Pennsylvania Geological Survey allowed us to use their chemical data collected from the Wissahickon Formation west of the Wilmington Complex, the Wilmington Complex, and the James Run Formation in Cecil County, Maryland (Smith and Barnes, 1994). The geochemistry of each rock unit is briefly discussed in this publication; detailed information will appear in a separate publication (Plank et al., in press).

On the basis of the geochemical data, we conclude that the rocks now mapped as Wilmington Complex formed over a subduction zone in an arc setting. The various mafic rocks in the Wilmington Complex represent a sequence of magmas and volcanics that originated early in the formation of the arc and during late extension within the arc. The arc was a product of subduction of oceanic crust beneath oceanic crust or beneath transitional crust with the overriding plate carrying an old volcanic arc, thinned continental crust, or rift sediments (Orndorff, 1999). In contrast, the mafic rocks in the Wissahickon Formation fall into two types: the Kennett Square amphibolites that are similar to N-MORBs and E-MORBs and formed as oceanic crust and the White Clay amphibolites that are products of intraplate volcanism, probably ocean island basalts. Thus, the mafic rocks of the Wilmington Complex originated in an arc setting, whereas the mafic rocks of the Wissahickon Formation originated in a marginal basin (Plank et al., in press).

DISCUSSION

Our model for the geologic history of the Delaware Piedmont is one of eastward dipping subduction and closure of a marginal basin bringing magmatic arc crust over marginal basin sediments, nearshore deposits, and continental crust during the Taconic orogeny. The metaigneous, metavolcanic, and igneous rocks of the Wilmington Complex represent the magmatic arc, the metasedimentary rocks of the Wissahickon Formation represent basin sediments, and the rocks of the Glenarm Group and Baltimore Gneiss represent Paleozoic nearshore deposits and continental crust of Grenville age, respectively.

Although penetrative deformation and upper amphibolite to granulite facies metamorphism have obscured most igneous fabrics and contact relationships in the Wilmington Complex, we believe the Brandywine Blue Gneiss, Barley Mill Gneiss, Montchanin Metagabbro, Mill Creek Metagabbro, and Christianstead Gneiss are metamorphosed

plutonic rocks, and the Rockford Park Gneiss, Faulkland Gneiss, and Windy Hills Gneiss are metamorphosed volcanic and volcanoclastic rocks.

The Brandywine Blue Gneiss and the Rockford Park Gneiss are the most intensely deformed and highly metamorphosed units in the Wilmington Complex and are the most difficult to interpret. The massive nature of the gneiss and rare metasedimentary enclaves that are possibly xenoliths of Wissahickon Formation (Srogi et al., 1993), indicate to us that the Brandywine Blue Gneiss was a pluton of intermediate tonalitic composition. The Rockford Park Gneiss is composed of laterally continuous layers of mafic and felsic gneiss of possible volcanic origin. Mafic layers in the Brandywine Blue Gneiss and the Rockford Park Gneiss have trace element compositions indicating both units are arc-related low K-tholeiites, but each are from a different magma source (Plank et al., in press). On the basis of their distinctive field characteristics and different chemistry, we have defined and mapped two separate lithodemes. The trace element compositions of the Rockford Park Gneiss are similar to modern boninites. In the western Pacific, the eruption of depleted boninitic lavas characterize early arc volcanism (Bloomer et al., 1995), thus the mafic layers in the Rockford Park Gneiss may be the product of early arc volcanism and is possibly of a different age than the felsic layers. Comparable dates of 476 ± 6 for the Brandywine Blue Gneiss and 476 ± 4 Ma for the felsic layers in the Rockford Park Gneiss suggest the felsic rocks may be related (John N. Aleinikoff, U. S. Geological Survey, personal communication, 2000). Our data support previous interpretations by Wagner and Srogi (1987) and Srogi et al. (1993, 1997) that these two units are deep-crustal remnants of a magmatic arc.

The Barley Mill Gneiss is a composite pluton composed of felsic gneiss with the composition of a tonalite, trondhjemite and granodiorite plus various amounts of amphibolite. Pelitic xenoliths of Wissahickon Formation in the Barley Mill Gneiss attest to the plutonic nature of this unit. In addition, outcrops of felsic gneiss with undeformed igneous textures and outcrops of interlayered and interfingered felsic gneiss and amphibolite supply possible evidence of magma mingling. The Barley Mill Gneiss has an igneous emplacement age of 470 ± 9 (John N. Aleinikoff, U. S. Geological Survey, personal communication, 2000). The Christianstead Gneiss is massive granitic gneiss with the composition of a granodiorite and an igneous emplacement age of 488 ± 8 (John N. Aleinikoff, U. S. Geological Survey, personal communication, 2000). The Montchanin Metagabbro and the Mill Creek Metagabbro are composed of coarse-grained amphibolites and less metamorphosed mafic rocks that are in part cumulates. We consider the three bodies of felsic gneiss plus the two bodies of metagabbro arc-related plutons.

The Faulkland Gneiss and the Windy Hills Gneiss are composed of amphibolite, quartz amphibolite, felsic gneiss, and biotite gneiss of igneous origin interlayered with quartzites and pelitic and psammitic rocks of sedimentary origin. The trace element composition of the amphibolite layers indicates an arc affinity (Plank et al., in press). We interpret this association of units as representative of volcanic and volcanoclastic rocks that were interlayered with sediments. At present we cannot separate the metasedimen-

tary rocks associated with these volcanic rocks from the metasedimentary rocks of the Wissahickon Formation; therefore, we have mapped all the metasediments as Wissahickon Formation.

Evidence for proposing a separate metasedimentary unit associated with the Wilmington Complex must be based on primary features such as bulk composition, distinctive sedimentary textures, different ages, or a major fault features that are commonly obliterated at high grades of metamorphism. Interlayered with and associated with the Wilmington Complex are a large-garnet \pm cordierite schist, a quartzofeldspathic gneiss and a garnet-orthopyroxene-bearing quartzite. These lithologies are different from the pelitic and psammitic lithologies that make up the bulk of the Wissahickon Formation west of the Wilmington Complex. However, we cannot demonstrate that the large-garnet schists and the quartzites are not the result of partial melting of pelitic units in the Wissahickon Formation during the very high temperature metamorphism that occurred in the rocks adjacent to the Wilmington Complex. A possible thrust contact between the "large garnet schist" and the psammitic gneiss of the Wissahickon Formation is marked in Wooddale and northeast of Hoopes Reservoir by thick mylonite layers (Bc52-a and Bc34-a). This mylonite may mark a thrust between the large garnet schist unit that is proximal to the arc and the more distal sediments of the Wissahickon Formation, but it is equally possible that the mylonite layers identify an internal thrust within the Wissahickon Formation. Isotopic ages, if available, might distinguish between older proximal forearc sediments and younger backarc sediments deposited during rifting. Identifying two units within the Wissahickon Formation would have important implications for a tectonic model; however, we do not have sufficient evidence to map separate units.

The Arden composite pluton, Bringhurst Gabbro, and Iron Hill Gabbro are most likely younger than the other units in the Wilmington Complex because igneous fabrics are preserved, and U-Pb ages on igneous zircons in the Arden composite pluton are reported to be 422 ± 6.5 Ma (Bosbyshell et al., 1998) and 434 ± 4 Ma (John N. Aleinikoff, U. S. Geological Survey, personal communication, 2000). Trace elements in the mafic rocks of the Arden composite pluton indicate the mafic rocks are similar to E-MORBs or back arc basin basalts (Plank et al., in press), therefore, we conclude the three plutons intruded during late-stage rifting within the arc.

The metasedimentary rocks and amphibolites of the Wissahickon Formation were deposited in a forearc basin. Geochemistry of the amphibolites indicates they were derived from a variety of magma sources. Type 1 amphibolite (White Clay amphibolite, R. C. Smith and J. H. Barnes, Pennsylvania Geological Survey, unpublished report, 1994) is enriched in Fe and Ti and has trace element compositions similar to intraplate basalts possibly seamounts formed in the forearc basin. Type 2 amphibolite (Kennett Square amphibolite, R. C. Smith and J. H. Barnes, Pennsylvania Geological Survey, unpublished report, 1994) has trace element compositions similar to MORBs and E-MORBs. Smith suggests the amphibolites are ocean floor basalts varying from N-MORBs on the east to E-MORBs in the west. A

similarity between the E-MORBS in the Arden composite pluton and the Wissahickon Formation suggests the E-MORBS erupted during rifting. A third type of amphibolite, the Smedley Park amphibolite, has been identified in the Wissahickon Formation in Pennsylvania. Trace element chemistry indicates it resembles E-MORBS but has volcanic arc characteristics as well (Bosbyshell et al., 2000).

In the area near Glenn Mills, Pennsylvania, and east of the Wilmington Complex H. Bosbyshell found a mafic dike with a distinctive boninitic composition virtually identical to mafic layers within the Rockford Park Gneiss (Bosbyshell et al. 1999, 2000). This dike intrudes and is deformed with pelitic layers of the Wissahickon Formation and a felsic orthogneiss that may be correlative with the Rockford Park Gneiss. This relationship suggests that the juxtaposition of the Wilmington Complex and the Wissahickon Formation occurred early in the geologic history of the region (Bosbyshell et al., 1999).

Metamorphism in the Delaware and southeastern Pennsylvania Piedmont varies from amphibolite to granulite grade. The highest grade of metamorphism is recorded in the Brandywine Blue Gneiss and the Rockford Park Gneiss in Delaware with intensity of metamorphism decreasing in all directions (Wycoff, 1952; Ward, 1959; Crawford and Mark, 1982; Wagner and Srogi, 1987; Alcock, 1989; Plank, 1989; Alcock and Wagner, 1995; Schenck and Plank, 1995; Bosbyshell et al., 1999; DGS Core and Sample Library). The decrease from granulite to amphibolite facies has also been recorded in the Brandywine Blue Gneiss and the Rockford Park Gneiss exposed to the north in Pennsylvania (Ward, 1959).

The systematic changes that reflect increasing intensity of metamorphism can be observed in the field as pelitic assemblages record the breakdown of muscovite to sillimanite and orthoclase, the breakdown of biotite and sillimanite to garnet, and the incongruent melting of biotite to garnet and cordierite. Mafic assemblages in the Wilmington Complex record the change from blue-green amphibole to brown amphibole to pyroxene. Precise estimates of peak temperatures are more difficult because the reaction temperatures are a function of water pressure, which is unknown and probably variable, and a higher pressure metamorphic overprinting is present in the Wissahickon east of the Wilmington Complex (Crawford and Mark, 1982; Bosbyshell, et al., 1999). Attempts to estimate peak metamorphic temperatures and pressures based on mineral assemblages in garnet-bearing biotite gneisses using petrogenetic grids and various geothermometers and geobarometers find:

- (1) Brandywine Blue Gneiss, Delaware, temperature of $800^{\circ}\pm 50^{\circ}$ C at pressure of 6 ± 1 kbars (Srogi, 1988; Wagner and Srogi, 1987; LeeAnn Srogi, personal communication, 2000);
- (2) Wissahickon Formation west of the Brandywine Blue Gneiss, temperatures of 620° to $750^{\circ}\pm 50^{\circ}$ C at pressures of 4 to 6 ± 1 kbars (Calem, 1987; Plank 1989; Alcock, 1989; Alcock and Wagner, 1995);
- (3) Wissahickon Formation east and adjacent to the Brandywine Blue gneiss, temperature approximately 700° C at pressures of 3 to 5 kbars (Crawford and Mark, 1982; Bosbyshell et al., 1999).

Earlier models attributed peak metamorphism in the Wissahickon Formation to overthrusting of a hot Wilmington Complex (Wagner and Srogi, 1987). On the basis of the interfingering of the Wissahickon Formation metasediments with the Wilmington Complex volcanic and volcanoclastic rocks and the small dike that intrudes both the Wissahickon Formation and Rockford Park Gneiss in Glenn Mills, we suggest the contact between the Wissahickon Formation and Wilmington Complex formed early in history of the arc and that the peak metamorphic event occurred during arc rifting. Isotopic evidence based on metamorphic zircons in the Brandywine Blue Gneiss constrains the metamorphic event to between 441 Ma (Grauert and Wagner, 1975; Wagner and Srogi, 1987) and 432 ± 6 Ma (John N. Aleinikoff, U. S. Geological Survey, personal communication, 2000). These ages are similar to the ages reported for the plutons associated with the rifting event at about 422 Ma (Bosbyshell et al., 1998) and about 434 Ma (John N. Aleinikoff, U. S. Geological Survey, personal communication, 2000) and suggest the granulite and amphibolite metamorphism is the result of high heat flow developed during arc rifting.

Previous studies have modeled the thrust emplacement of the Wissahickon Formation and the folding and thrusting of the Mill Creek Nappe as events that occurred during north-west directed Taconic compression. These events probably represent a continuum beginning with the deformation of the Baltimore Gneiss, the Glenarm units, and the Wissahickon Formation. As subduction closed the forearc basin between the magmatic arc and ancient continent, Wissahickon sediments were thrust over developing nappes in the Baltimore Gneiss and its Glenarm cover. Folding continued and this initial thrust contact was also folded. In a final compressional event, a thrust developed that cut the first thrust and brought the Baltimore Gneiss and Glenarm Group over Wissahickon to the northwest (Alcock, 1989, 1991, and 1994; Woodruff and Plank, 1995; Plank and Schenck, 1997).

CONCLUSIONS

In this report we have formally named eleven new rock units, informally recognized two rock units, and redefined previously mapped rock units in the Delaware and southeastern Pennsylvania Piedmont. We have redefined the Wilmington Complex to include all rocks associated with the development of a Paleozoic magmatic arc; five metaplutonic lithodemes recognized and herein named the Brandywine Blue Gneiss, Montchanin Metagabbro, Mill Creek Metagabbro, Barley Mill Gneiss, and the Christianstead Gneiss; three metavolcanic units, the Windy Hills Gneiss, Faulkland Gneiss, and the Rockford Park Gneiss; three igneous plutons, the redefined Arden Plutonic Supersuite (comprising the Ardentown Granitic Suite, Perkins Run Gabbro, and one lithodeme of biotite tonalite), the Bringhurst Gabbro, and Iron Hill Gabbro.

With the help of John N. Aleinikoff, U. S. Geological Survey, we were able to get U-Pb ages on seven rock units. U-Pb ages on zircons found in the Arden Supersuite are reported at 434 ± 4 Ma, the Brandywine Blue Gneiss at 476 ± 6 Ma, the Rockford Park Gneiss at 476 ± 4 Ma, the Faulkland Gneiss at 482 ± 4 Ma, the Windy Hills Gneiss at 481 ± 4 Ma, the Barley Mill Gneiss at 470 ± 9 Ma, and the Christianstead Gneiss at 488 ± 8 Ma. The James Run Formation in the type locality near Baltimore, Maryland is

dated at 450 to 465 Ma (Horton et al, 1998). This is significantly younger than the 470 to 488 Ma ages reported for the Wilmington Complex. Thus, we have separated the James Run Formation from the Wilmington Complex and suggest the Cecil County volcanic complex assigned to the James Run Formation by Higgins in 1972 may be equivalent to the Wilmington Complex.

The Wissahickon Formation includes a lens of ultramafic and mafic rocks, probably a sliver of an ophiolite, and a thin Mesozoic diabase dike. This unit comprises the sediments that accumulated in a forearc basin including N-MORBS, E-MORBS, and intraplate basalts.

The oldest rocks are Grenville-age layered gneisses, migmatites, and amphibolites named the Baltimore Gneiss. The Baltimore Gneiss is exposed in the cores of the two antiformal structures of the Mill Creek Nappe.

The Appalachian Piedmont Province of Delaware and adjacent Pennsylvania records the collision of an offshore magmatic arc with the ancient North American continent during the Ordovician Taconic orogeny. As a result of this collision the rocks are complexly deformed and at upper amphibolite and granulite facies of metamorphism.

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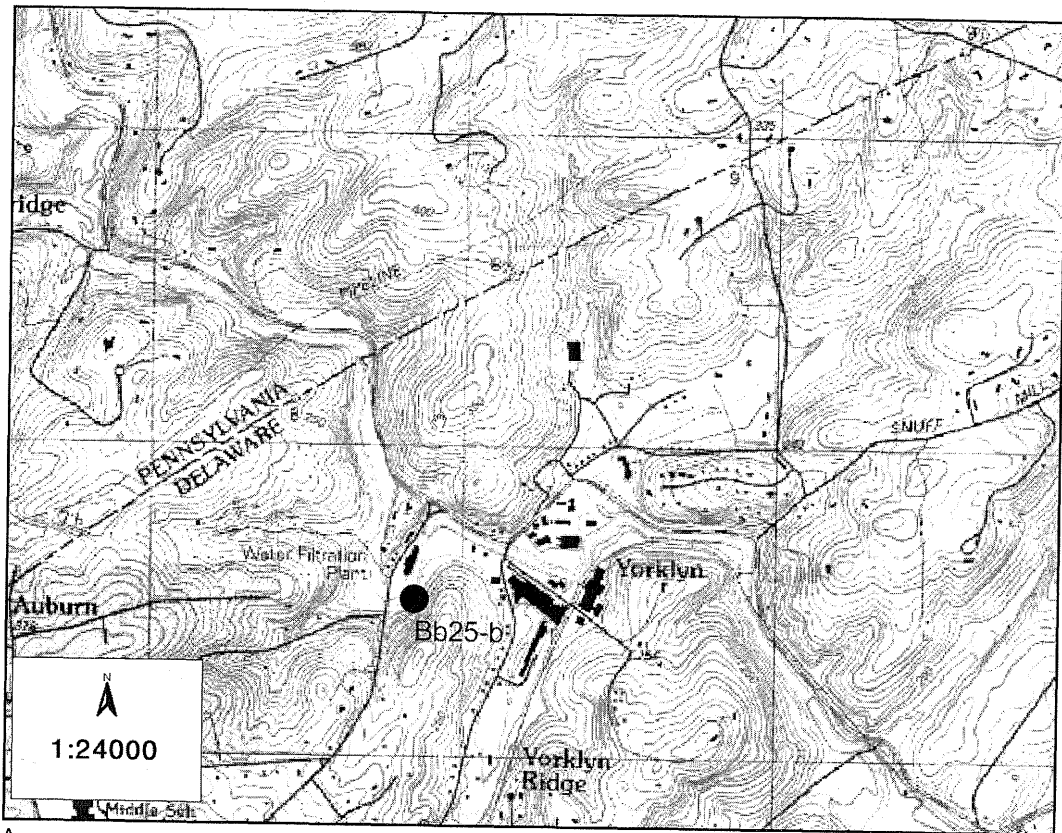
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APPENDIX
TYPE AND REFERENCE SECTION LOCATION MAPS AND LITHOLOGIES

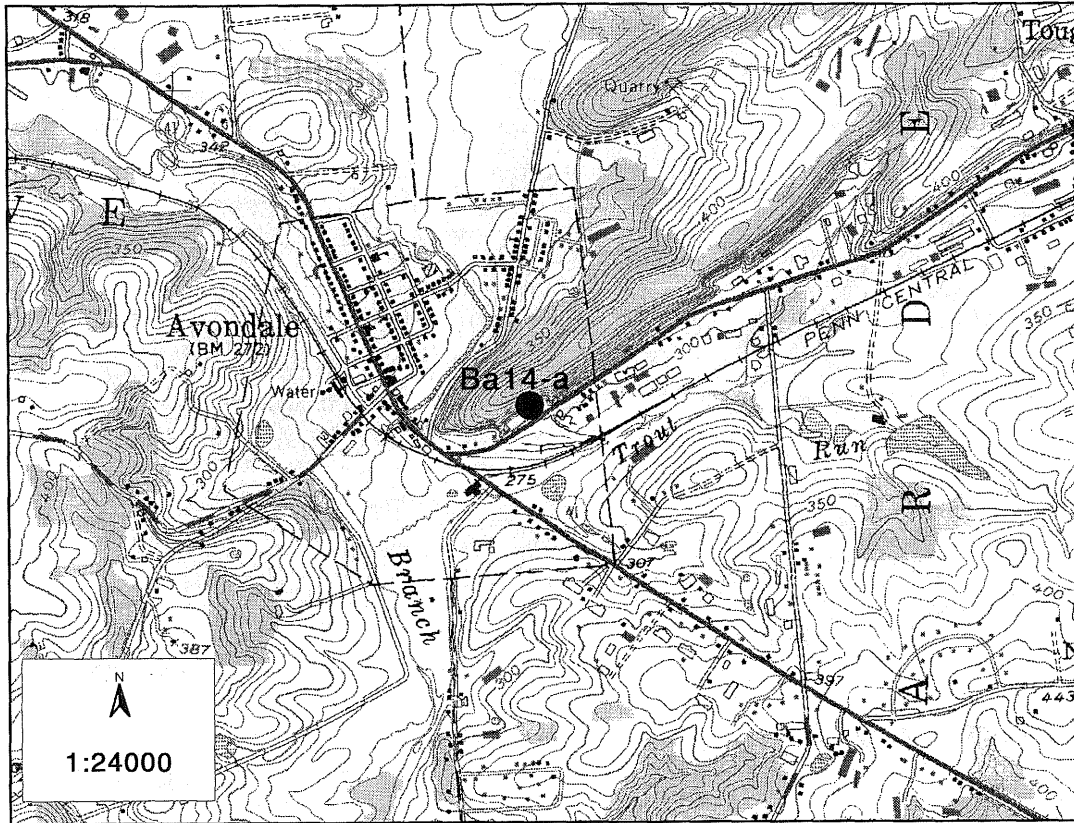


A.

| DGSID | LAT* | LON* | LITHOLOGY |
|--------|----------|----------|----------------------------|
| Bb25-b | 39 48 23 | 75 40 47 | Amphibolite, Felsic Gneiss |

* Latitudes and longitudes are in NAD27

Reference section outcrop location map and lithologies for the Baltimore Gneiss in Delaware. Map is taken from the U.S. Geological Survey Kennett Square 7.5-minute quadrangle. Many type and reference sections for rock units are on private property. Permission to access these outcrops should always be obtained before visiting.

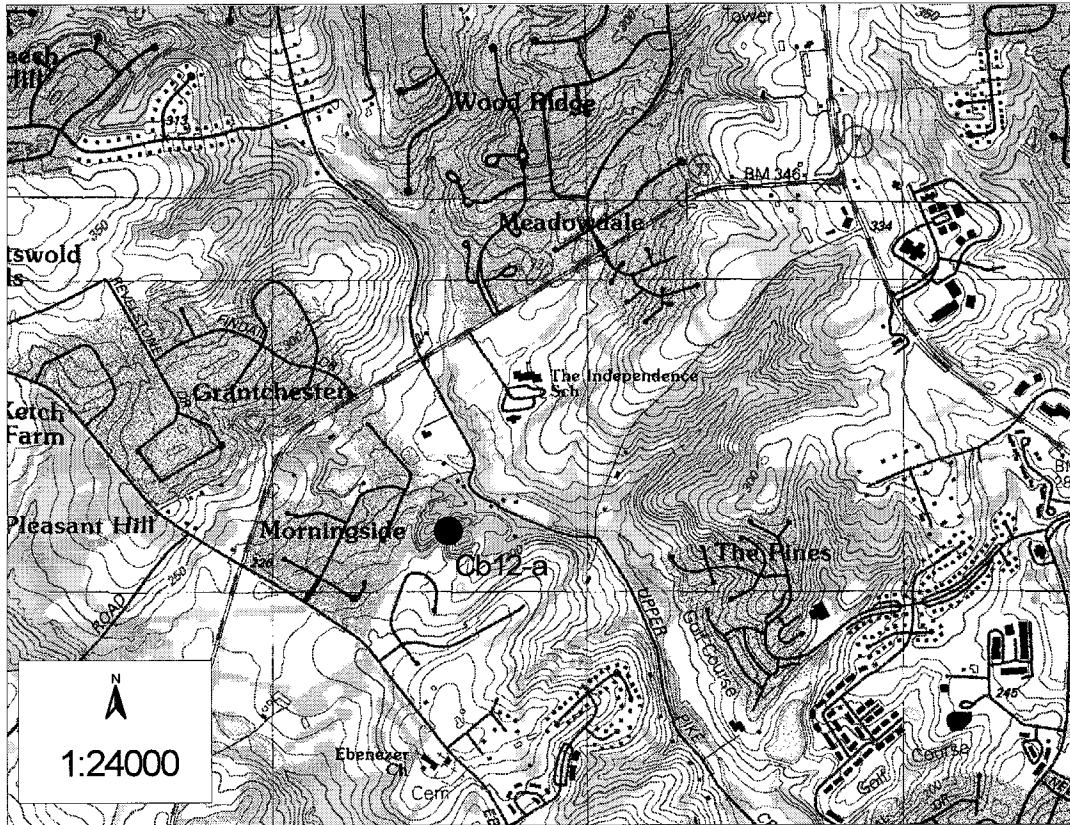


B.

| DGSID | LAT* | LON* | LITHOLOGY |
|--------|----------|----------|------------------------------|
| Ba14-a | 39 49 36 | 75 46 35 | Psammitic and Pelitic Gneiss |

* Latitudes and longitudes are in NAD27

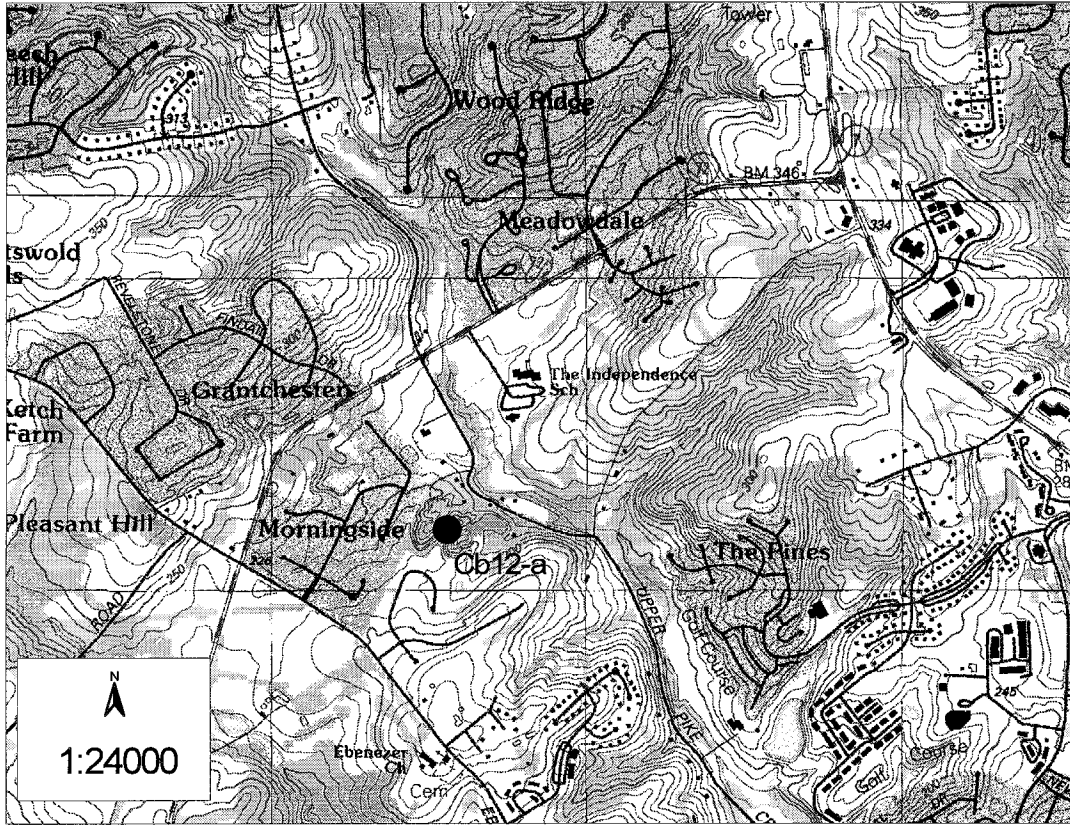
Reference section outcrop location map and lithologies for the Setters Formation in Pennsylvania. Map is taken from the U.S. Geological Survey West Grove 7.5-minute quadrangle. Many type and reference sections for rock units are on private property. Permission to access these outcrops should always be obtained before visiting.



| DGSID | LAT* | LON* | LITHOLOGY |
|--------|----------|----------|----------------|
| Cb12-a | 39 44 25 | 75 43 03 | Pelitic Schist |

* Latitudes and longitudes are in NAD27

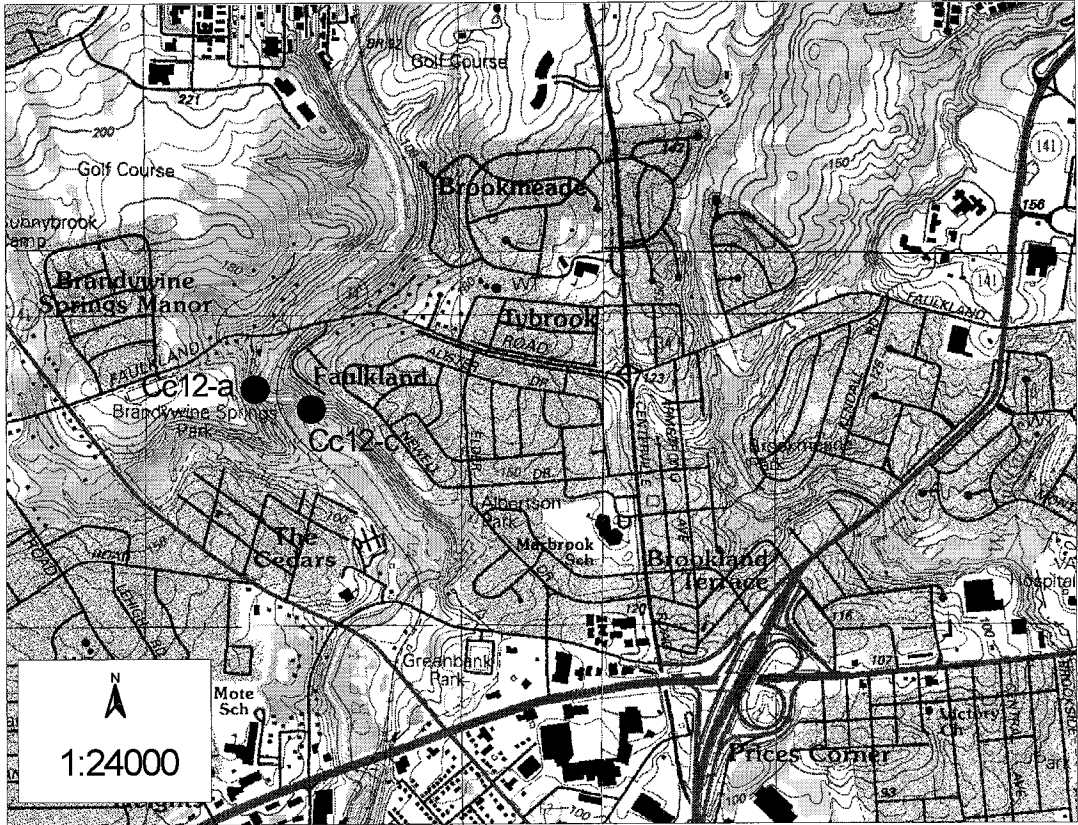
Reference section outcrop location map and lithologies for the Setters Formation in Delaware. Map is taken from the U.S. Geological Survey Newark East 7.5-minute quadrangle. Many type and reference sections for rock units are on private property. Permission to access these outcrops should always be obtained before visiting.



| DGSID | LAT* | LON* | LITHOLOGY |
|--------|----------|----------|-----------|
| Cb12-a | 39 44 25 | 75 43 03 | Marble |

* Latitudes and longitudes are in NAD27

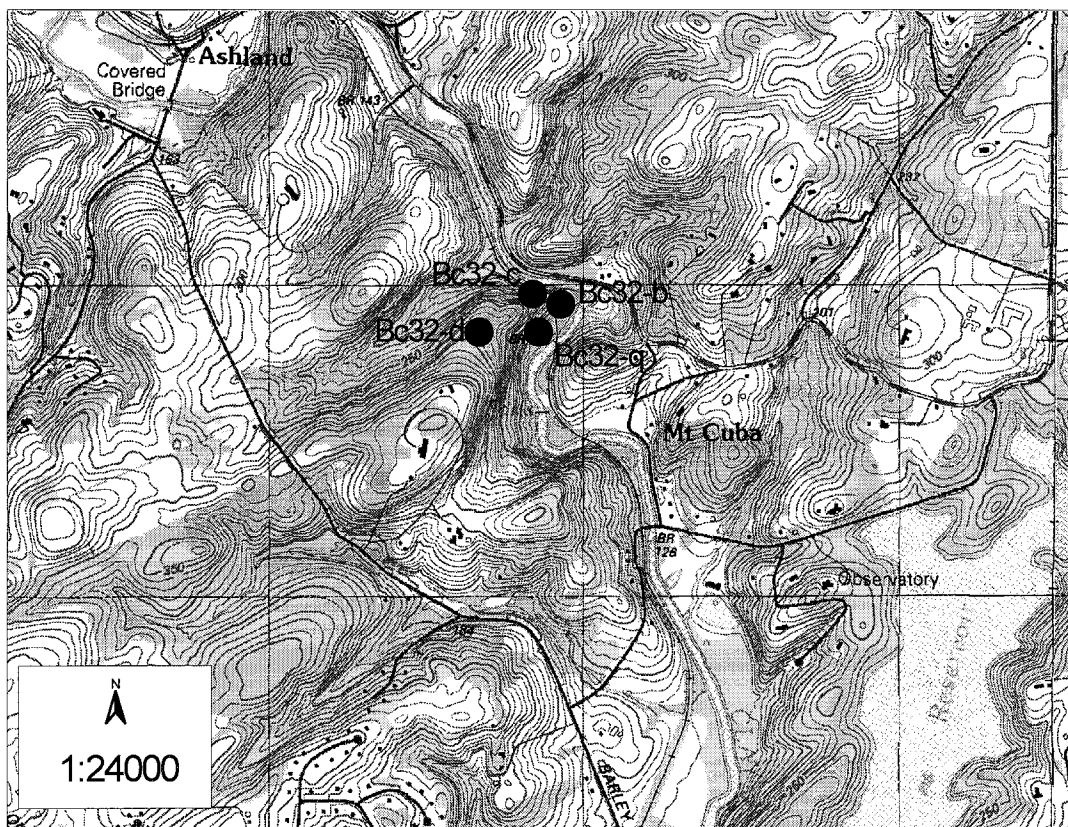
Reference section outcrop location map and lithologies for the Cockeysville Marble in Delaware. Map is taken from the U.S. Geological Survey Newark East 7.5-minute quadrangle. Many type and reference sections for rock units are on private property. Permission to access these outcrops should always be obtained before visiting.



| DGSID | LAT* | LON* | LITHOLOGY |
|--------|----------|----------|---------------------------|
| Cc12-a | 39 44 45 | 75 38 18 | Pelitic Gneiss, Quartzite |
| Cc12-c | 39 44 43 | 75 38 10 | Pelitic Gneiss, Quartzite |

* Latitudes and longitudes are in NAD27

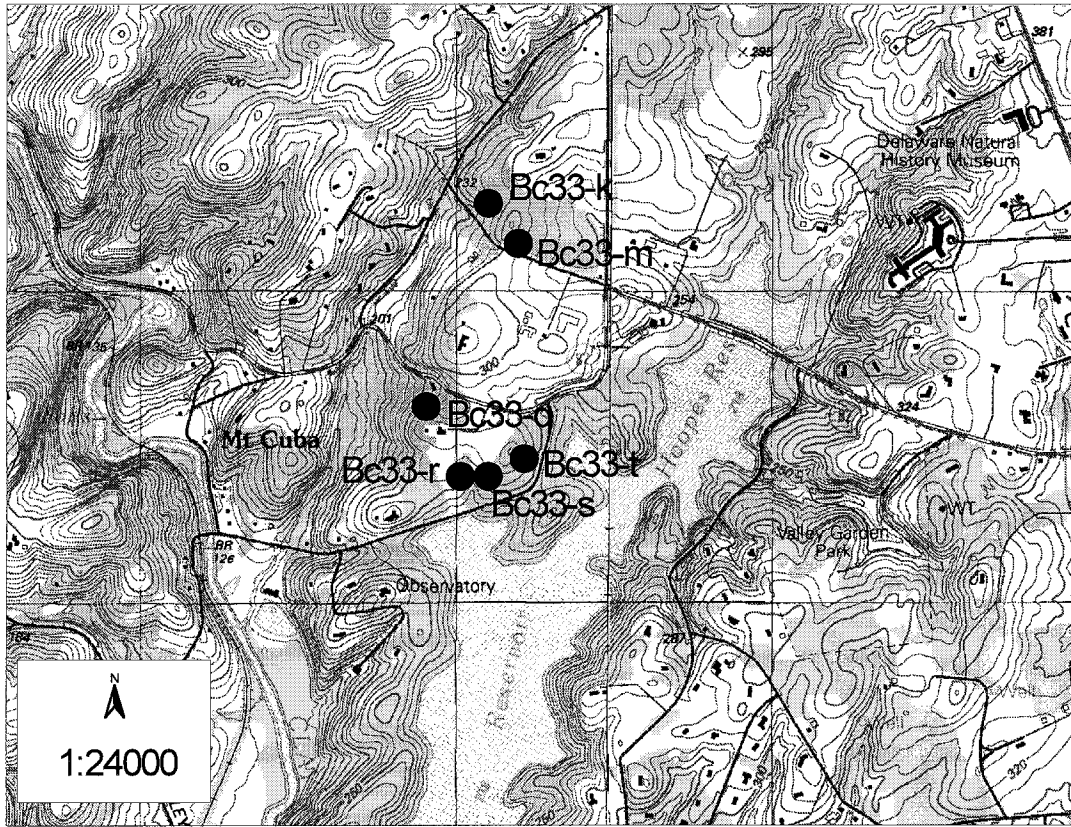
Reference section outcrop location map and lithologies for the Wissahickon Formation near Brandywine Springs Park, Delaware. Map is taken from the U.S. Geological Survey Kennett Square, Wilmington North, Newark East, and Wilmington South 7.5-minute quadrangles. Many type and reference sections for rock units are on private property. Permission to access these outcrops should always be obtained before visiting.



| DGSID | LAT* | LON* | LITHOLOGY |
|--------|----------|----------|---|
| Bc32-b | 39 47 33 | 75 38 37 | Pelitic Gneiss |
| Bc32-c | 39 47 34 | 75 38 41 | Pssamitic Gneiss |
| Bc32-d | 39 47 30 | 75 38 48 | Pelitic Gneiss With Sillimanite Nodules |
| Bc32-q | 39 47 30 | 75 38 40 | Amphibolite |

* Latitudes and longitudes are in NAD27

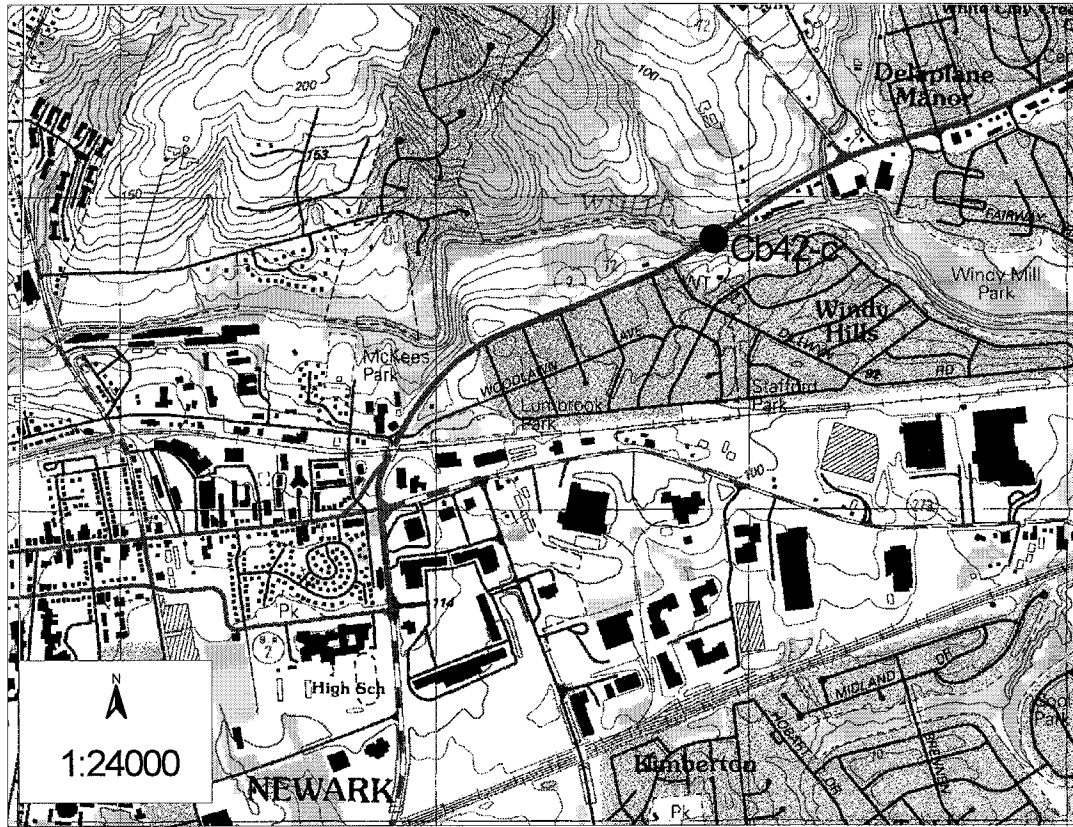
Reference section outcrop location map and lithologies for the Wissahickon Formation at Mt. Cuba, Delaware. Map is taken from the U.S. Geological Survey Kennett Square and Wilmington North 7.5-minute quadrangles. Many type and reference sections for rock units are on private property. Permission to access these outcrops should always be obtained before visiting.



| DGSID | LAT* | LOX* | LITHOLOGY |
|--------|----------|----------|------------------------------|
| Bc33-k | 39 47 44 | 75 37 48 | Hornblende Metagabbro |
| Bc33-m | 39 47 46 | 75 37 38 | Hornblende Metagabbro |
| Bc33-q | 39 47 23 | 75 37 56 | Amphibolite (Metapyroxenite) |
| Bc33-r | 39 47 16 | 75 37 51 | Serpentinite |
| Bc33-s | 39 47 16 | 75 37 47 | Serpentinite |
| Bc33-t | 39 47 18 | 75 37 43 | Amphibolite (Metapyroxenite) |

* Latitudes and longitudes are in NAD27

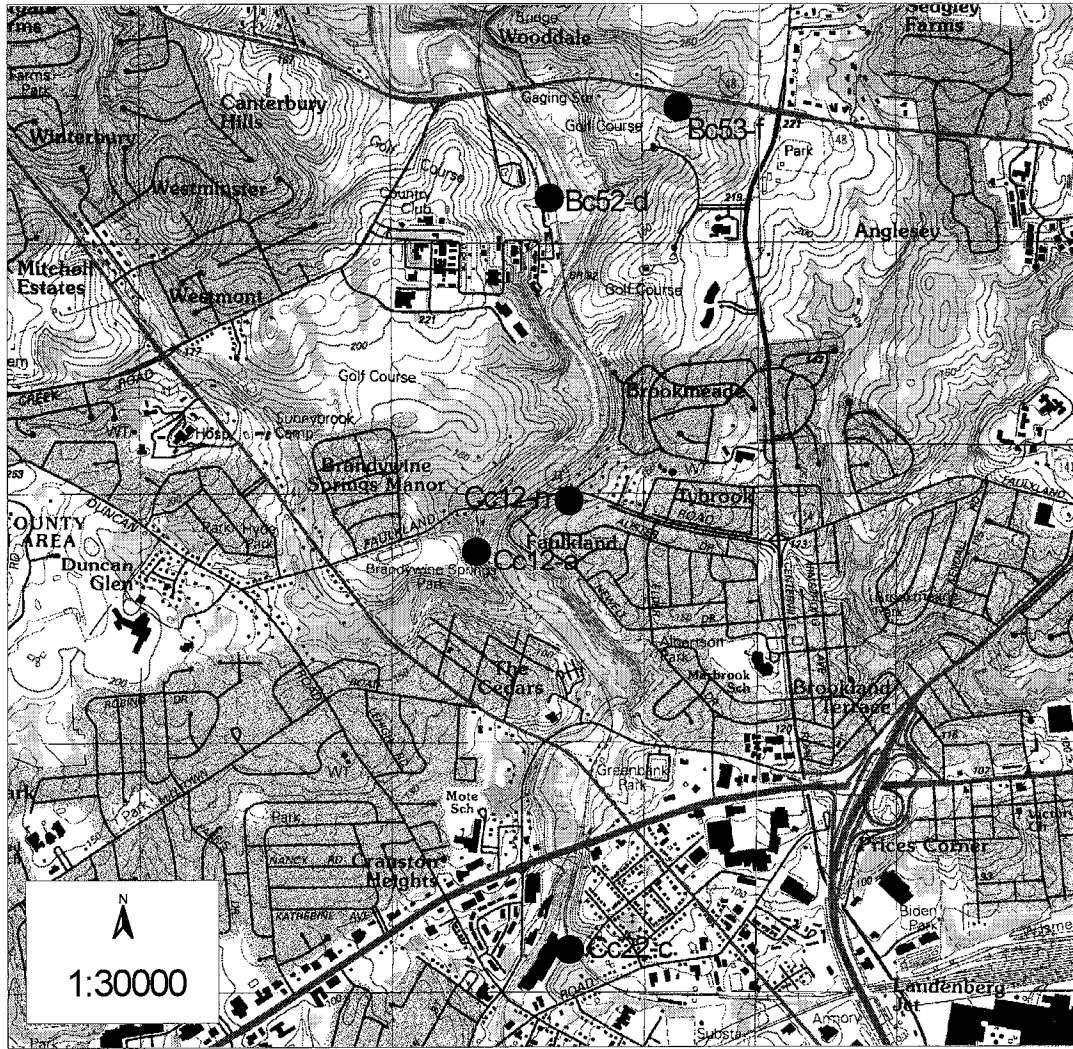
Type section outcrop location map and lithologies for the ultramafic lens. Map is taken from the U.S. Geological Survey Kennett Square and Wilmington North 7.5-minute quadrangles. Many type and reference sections for rock units are on private property. Permission to access these outcrops should always be obtained before visiting.



| DGSID | LAT* | LON* | LITHOLOGY |
|--------|----------|----------|--------------------------------------|
| Cb42-c | 39 41 32 | 75 43 29 | Interlayered Mafic and Felsic Gneiss |

* Latitudes and longitudes are in NAD27

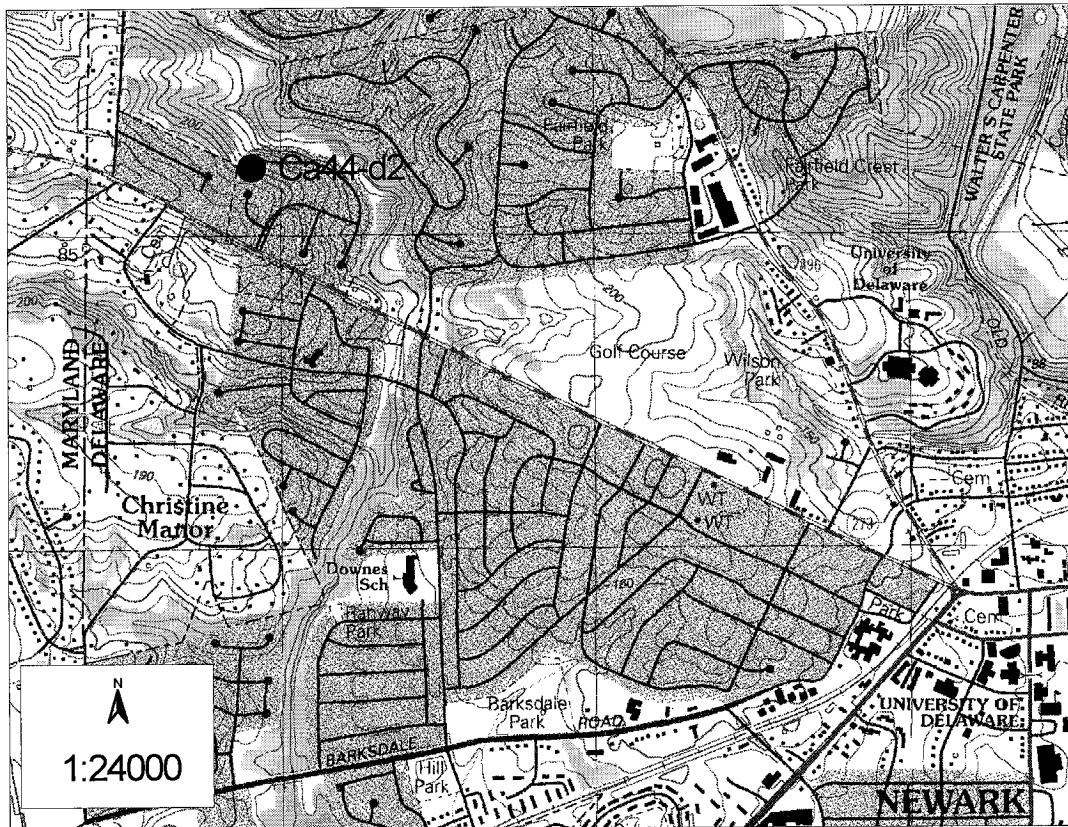
Reference section outcrop location map and lithologies for the Windy Hills Gneiss. Map is taken from the U.S. Geological Survey Newark East 7.5-minute quadrangle. Many type and reference sections for rock units are on private property. Permission to access these outcrops should always be obtained before visiting.



| DGSID | LAT* | LON* | LITHOLOGY |
|--------|----------|----------|---------------------------|
| Bc53-f | 39 45 43 | 75 37 45 | Felsic Gneiss |
| Bc52-d | 39 45 31 | 75 38 06 | Hornblendite |
| Cc12-n | 39 44 52 | 75 38 03 | Amphiboite |
| Cc12-a | 39 44 45 | 75 38 18 | Cummingtonite Amphibolite |
| Cc22-c | 39 43 54 | 75 38 02 | Quartz Amphibolite |

* Latitudes and longitudes are in NAD27

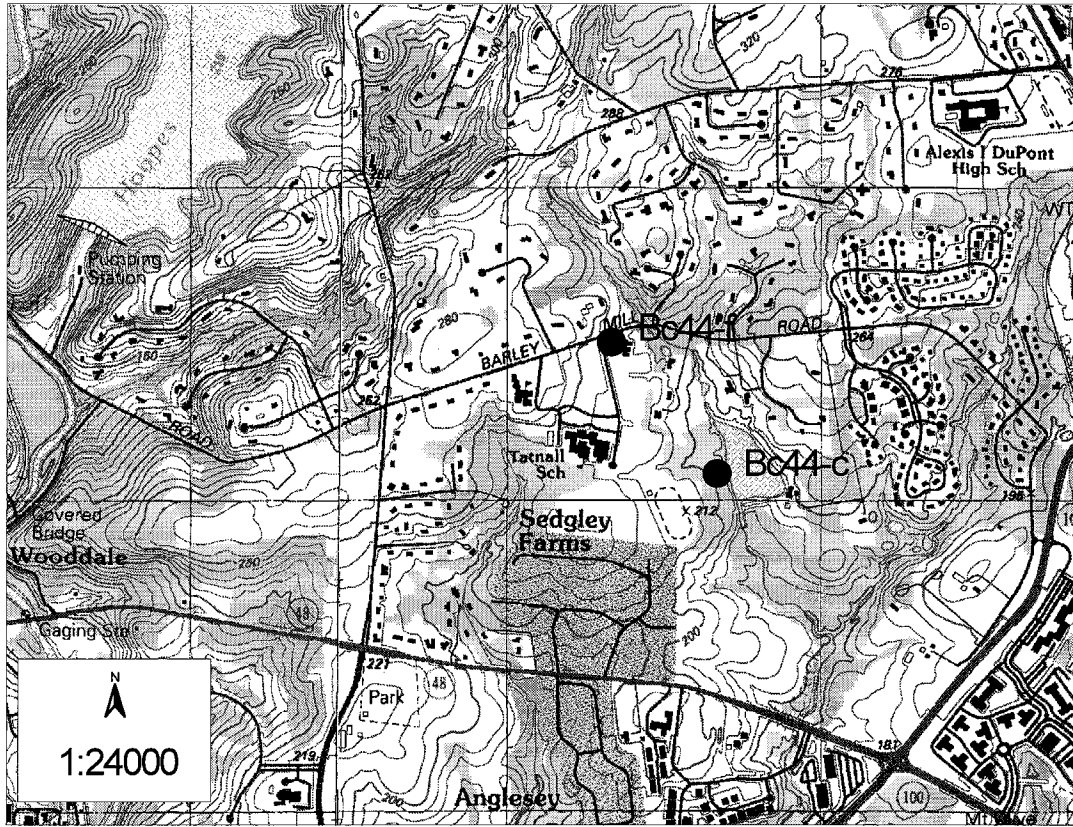
Type section outcrop location map and lithologies for the Faulkland Gneiss. Map is taken from the U.S. Geological Survey Kennett Square, Wilmington North, Wilmington South, and Newark East 7.5-minute quadrangles. Many type and reference sections for rock units are on private property. Permission to access these outcrops should always be obtained before visiting.



| DGSID | LAT* | LON* | LITHOLOGY |
|---------|----------|----------|--------------|
| Ca44-d2 | 39 41 42 | 75 46 58 | Granodiorite |

* Latitudes and longitudes are in NAD27

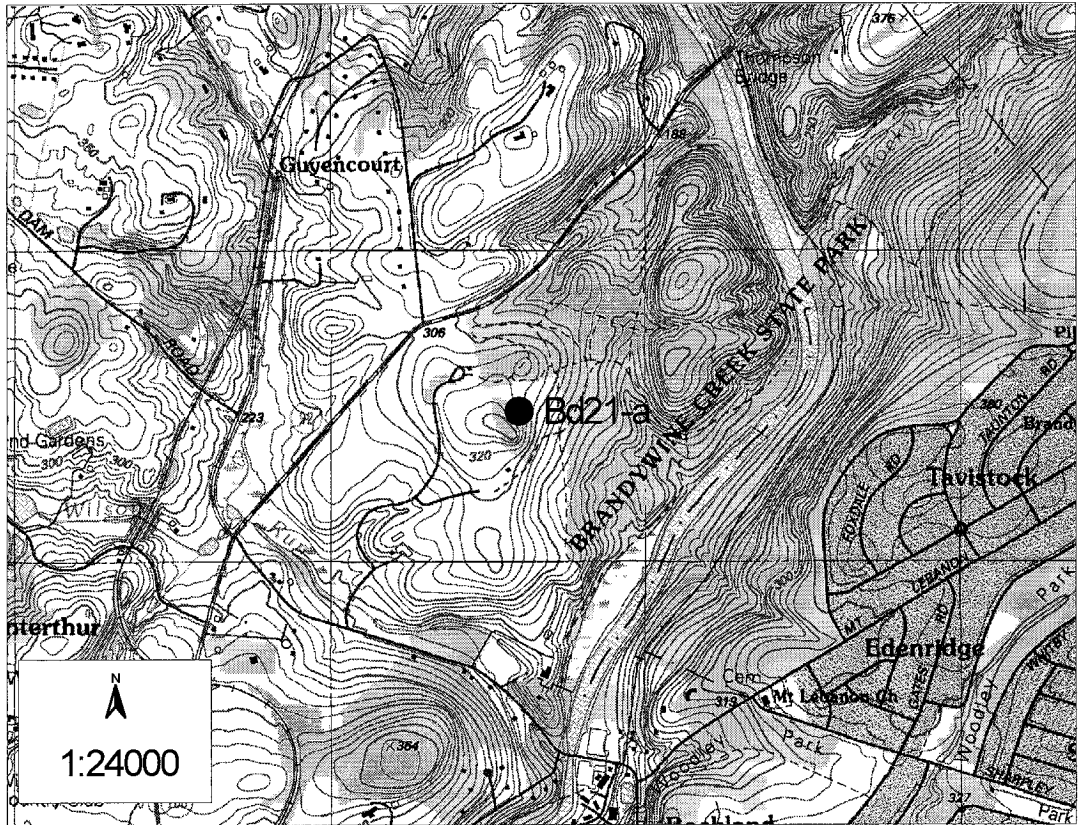
Type section outcrop location map and lithologies for the Christianstead Gneiss. Map is taken from the U.S. Geological Survey Newark West 7.5-minute quadrangle. Many type and reference sections for rock units are on private property. Permission to access these outcrops should always be obtained before visiting.



| DGSID | LAT* | LON* | LITHOLOGY |
|--------|----------|----------|-----------------|
| Bc44-f | 39 46 16 | 75 36 56 | Tonalite Gneiss |
| Bc44-c | 39 46 01 | 75 36 40 | Tonalite Gneiss |

* Latitudes and longitudes are in NAD27

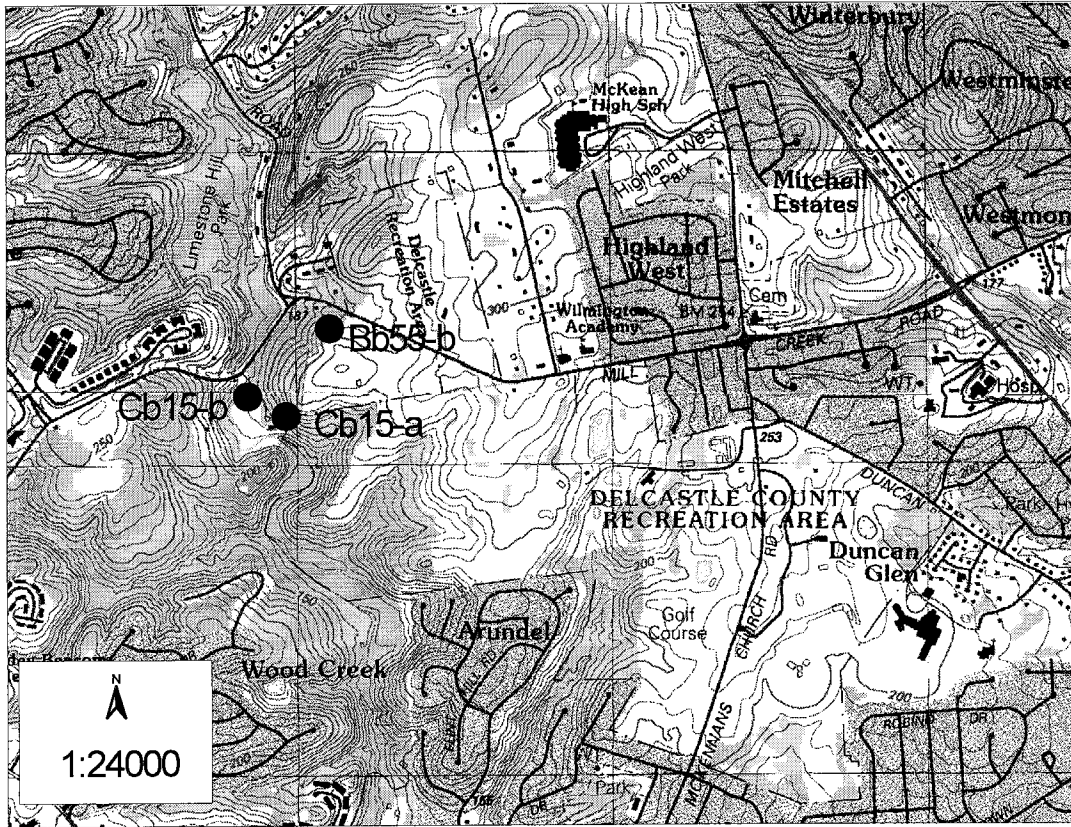
Type section outcrop location map and lithologies for the Barley Mill Gneiss. Map is taken from the U.S. Geological Survey Kennett Square and Wilmington North 7.5-minute quadrangles. Many type and reference sections for rock units are on private property. Permission to access these outcrops should always be obtained before visiting.



| DGSID | LAT* | LON* | LITHOLOGY |
|--------|----------|----------|--------------------------|
| Bd21-a | 39 48 24 | 75 34 39 | Amphibolite (Metagabbro) |

* Latitudes and longitudes are in NAD27

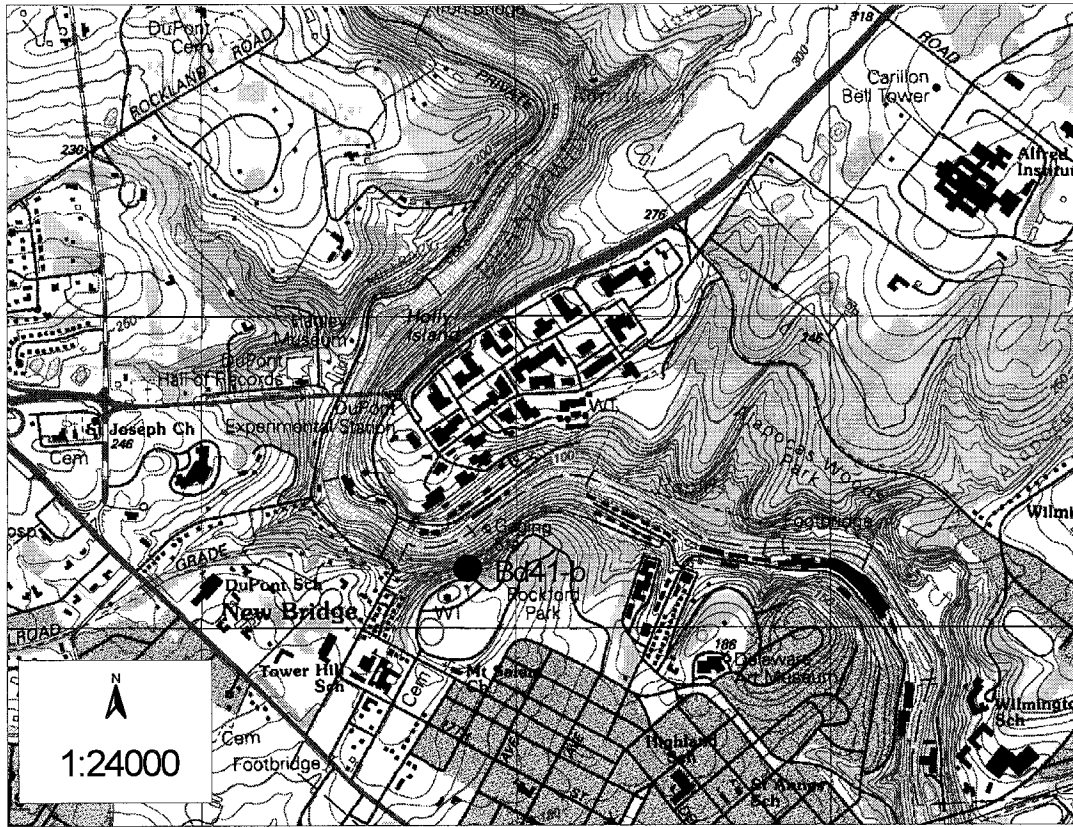
Type section outcrop location map and lithologies for the Montchanin Metagabbro. Map is taken from the U.S. Geological Survey Wilmington North 7.5-minute quadrangle. Many type and reference sections for rock units are on private property. Permission to access these outcrops should always be obtained before visiting.



| DGSID | LAT* | LON* | LITHOLOGY |
|--------|----------|----------|-------------|
| Cb15-a | 39 44 57 | 75 40 40 | Amphibolite |
| Cb15-b | 39 44 59 | 75 40 45 | Amphibolite |
| Bb55-b | 39 45 06 | 75 40 34 | Amphibolite |

* Latitudes and longitudes are in NAD27

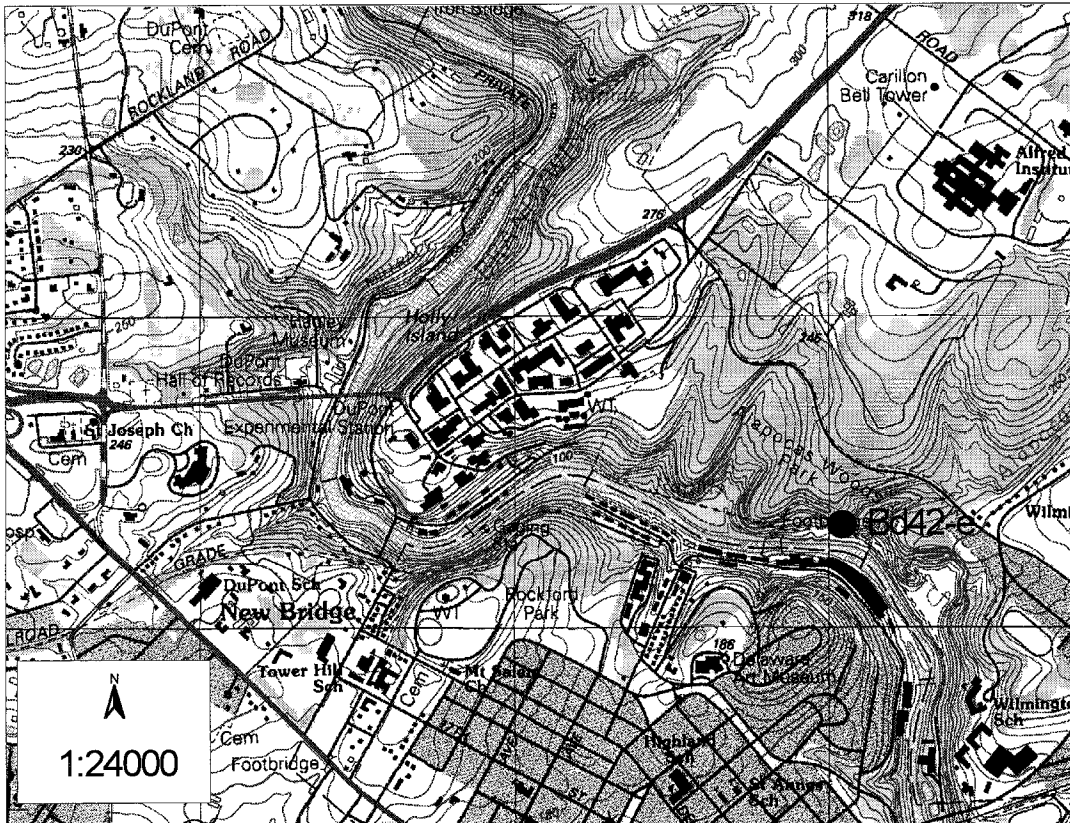
Type section outcrop location map and lithologies for the Mill Creek Metagabbro. Map is taken from the U.S. Geological Survey Newark East and Kennett Square 7.5-minute quadrangles. Many type and reference sections for rock units are on private property. Permission to access these outcrops should always be obtained before visiting.



| DGSID | LAT* | LON* | LITHOLOGY |
|--------|----------|----------|-------------------------|
| Bd41-b | 39 46 05 | 75 34 27 | Mafic and Felsic Gneiss |

* Latitudes and longitudes are in NAD27

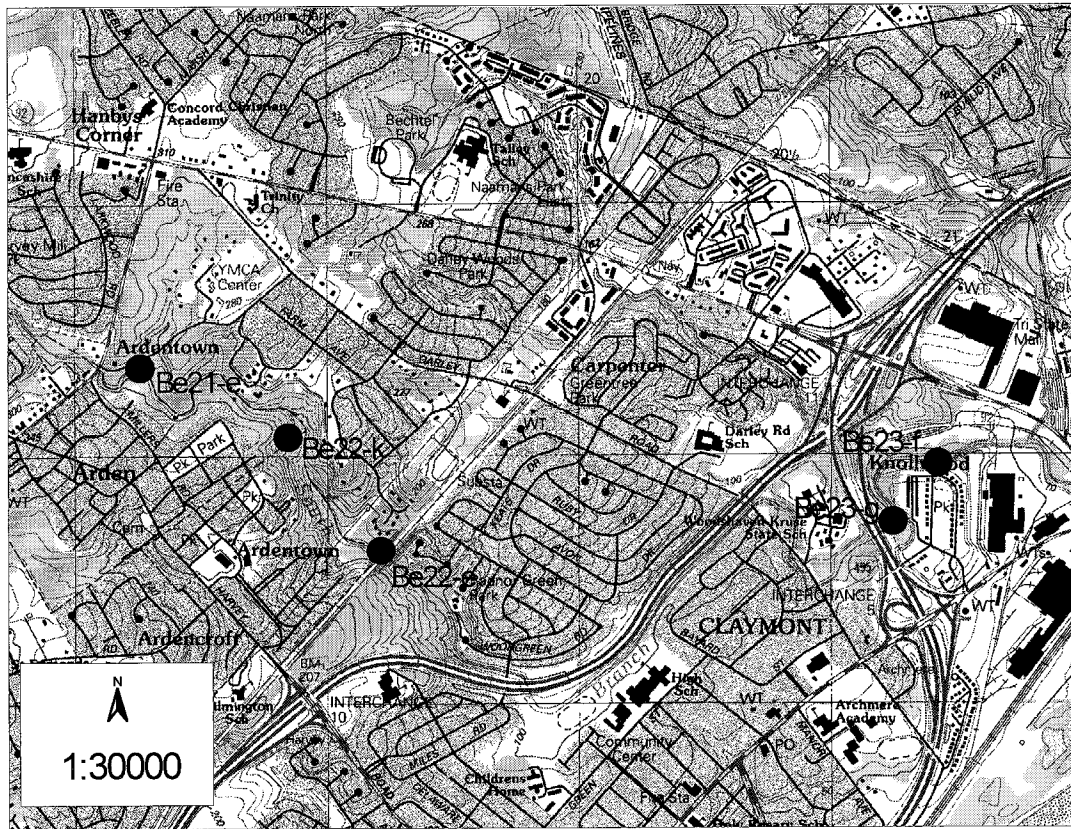
Type section outcrop location map and lithologies for the Rockford Park Gneiss. Map is taken from the U.S. Geological Survey Wilmington North 7.5-minute quadrangle. Many type and reference sections for rock units are on private property. Permission to access these outcrops should always be obtained before visiting.



| DGSID | LAT* | LON* | LITHOLOGY |
|--------|----------|----------|---------------|
| Bd42-e | 39 46 10 | 75 33 37 | Felsic Gneiss |

* Latitudes and longitudes are in NAD27

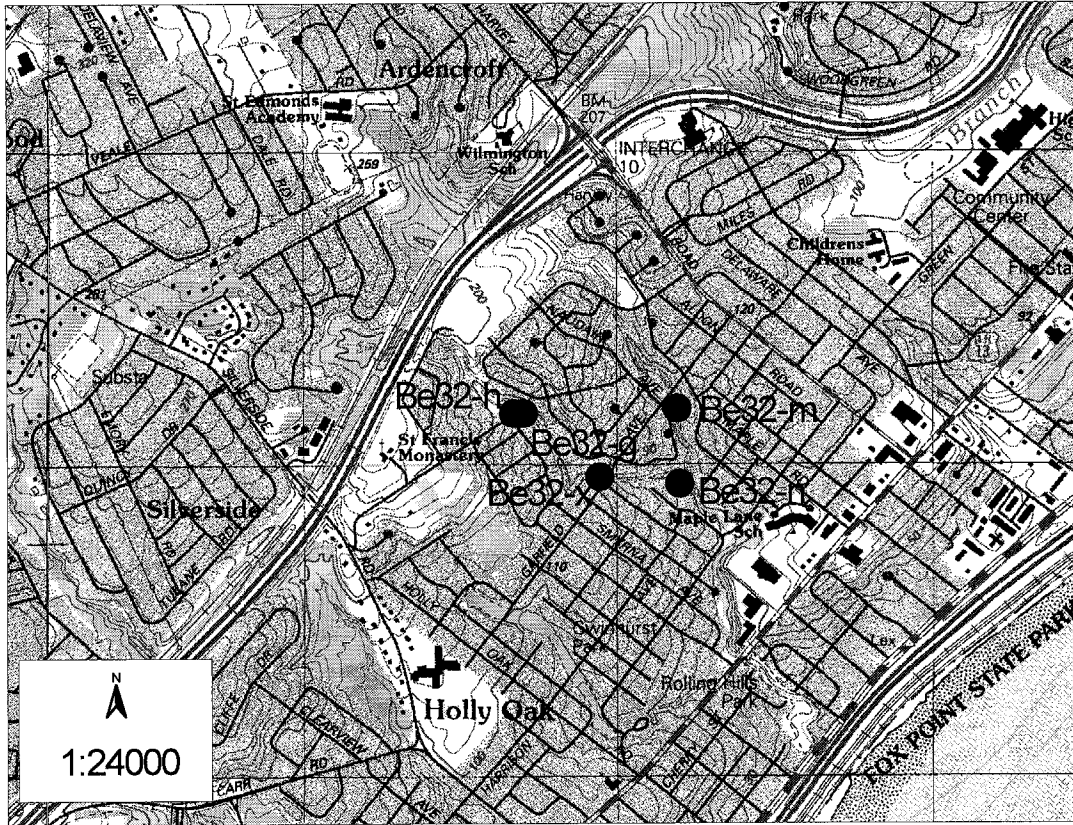
Type section outcrop location map and lithologies for the Brandywine Blue Gneiss. Map is taken from the U.S. Geological Survey Wilmington North 7.5-minute quadrangle. Many type and reference sections for rock units are on private property. Permission to access these outcrops should always be obtained before visiting.



| DGSID | LAT* | LON* | LITHOLOGY |
|--------|----------|----------|--------------------------------------|
| Be21-e | 39 48 54 | 75 29 17 | Charnockite |
| Be22-e | 39 48 30 | 75 28 37 | Opdalite |
| Be22-k | 39 48 45 | 75 28 52 | Quartz Norite and Quartz Monzonorite |
| Be23-f | 39 48 42 | 75 27 04 | Quartz Norite and Quartz Monzonorite |
| Be23-g | 39 48 34 | 75 27 11 | Quartz Norite and Quartz Monzonorite |

* Latitudes and longitudes are in NAD27

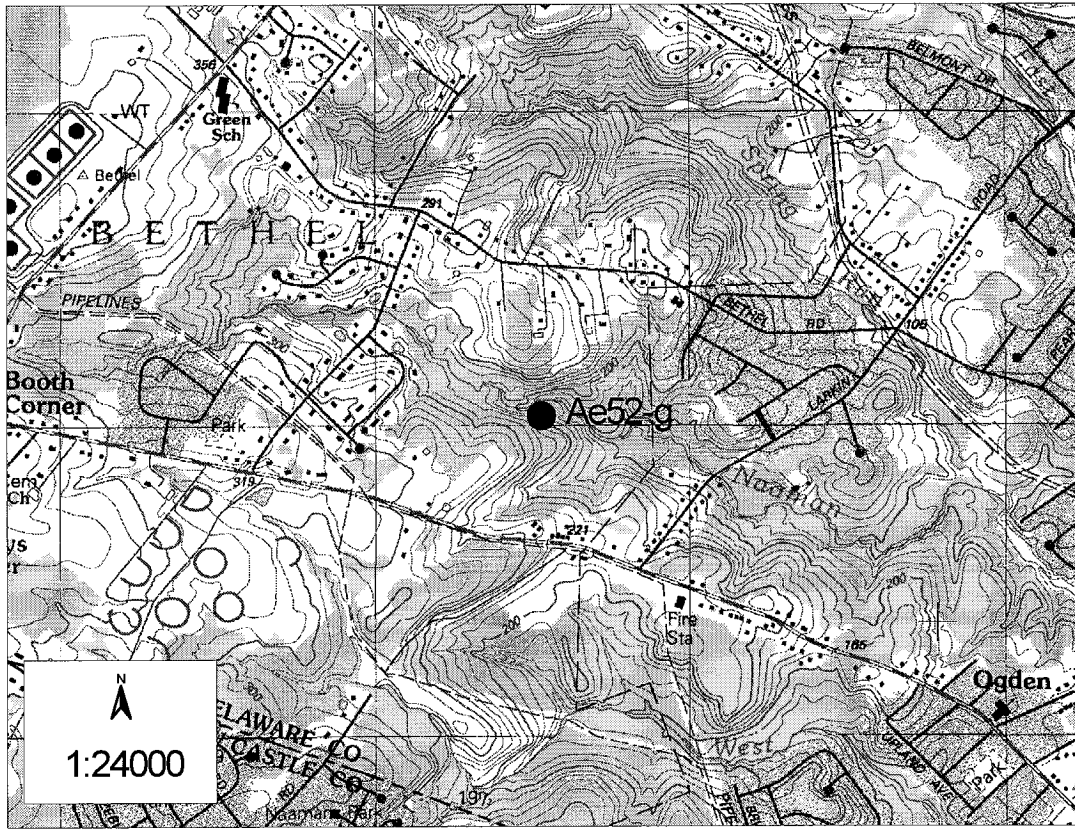
Type section outcrop location map and lithologies for the Arden Plutonic Supersuite Ardentown Granitic Suite. Map is taken from the U.S. Geological Survey Marcus Hook 7.5-minute quadrangle. Many type and reference sections for rock units are on private property. Permission to access these outcrops should always be obtained before visiting.



| DGSID | LAT* | LON* | LITHOLOGY |
|--------|----------|----------|---------------------------|
| Be32-g | 39 47 43 | 75 28 58 | Foliated Gabbroonrite |
| Be32-h | 39 47 43 | 75 28 59 | Foliated Gabbroonrite |
| Be32-m | 39 47 44 | 75 28 37 | Foliated Gabbroonrite |
| Be32-n | 39 47 36 | 75 28 37 | Gabbroonrite +/- Olivine |
| Be32-x | 39 47 36 | 75 28 47 | Fine-Grained Gabbroonrite |

* Latitudes and longitudes are in NAD27

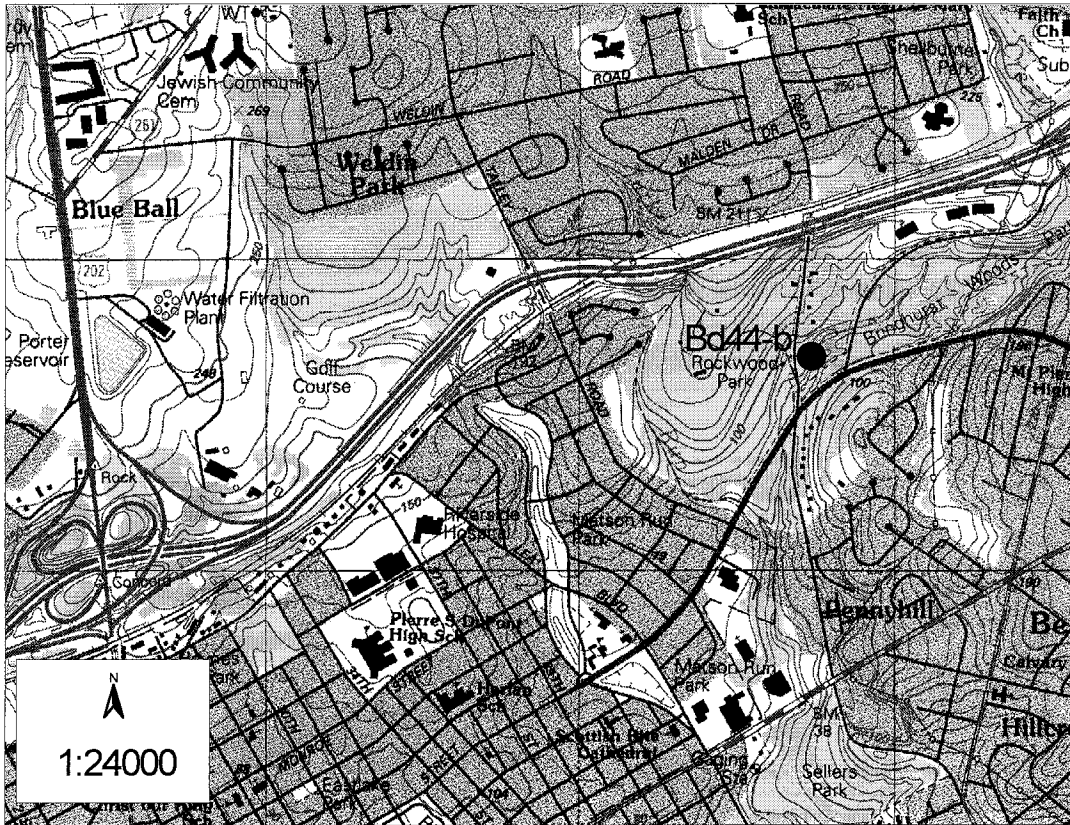
Type section outcrop location map and lithologies for the Arden Plutonic Supersuite Perkins Run Gabbroonrite Suite. Map is taken from the U.S. Geological Survey Marcus Hook 7.5-minute quadrangle. Many type and reference sections for rock units are on private property. Permission to access these outcrops should always be obtained before visiting.



| DGSID | LAT* | LON* | LITHOLOGY |
|--------|----------|----------|------------------|
| Ae52-g | 39 50 21 | 75 28 24 | Biotite Tonalite |

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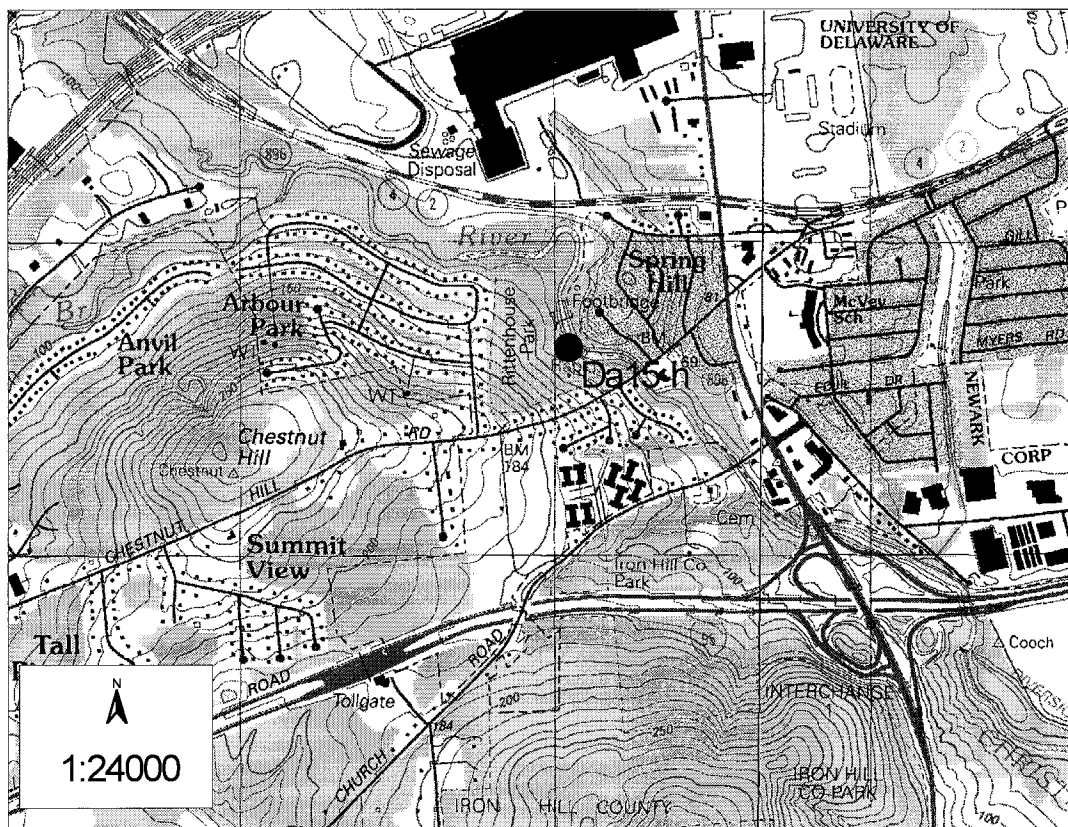
Type section outcrop location map and lithologies for the Arden Plutonic Supersuite biotite tonalite lithodeme. Map is taken from the U.S. Geological Survey Marcus Hook 7.5-minute quadrangle. Many type and reference sections for rock units are on private property. Permission to access these outcrops should always be obtained before visiting.



| DGSID | LAT* | LON* | LITHOLOGY |
|--------|----------|----------|--------------|
| Bd44-b | 39 46 41 | 75 31 55 | Gabbronorite |

* Latitudes and longitudes are in NAD27

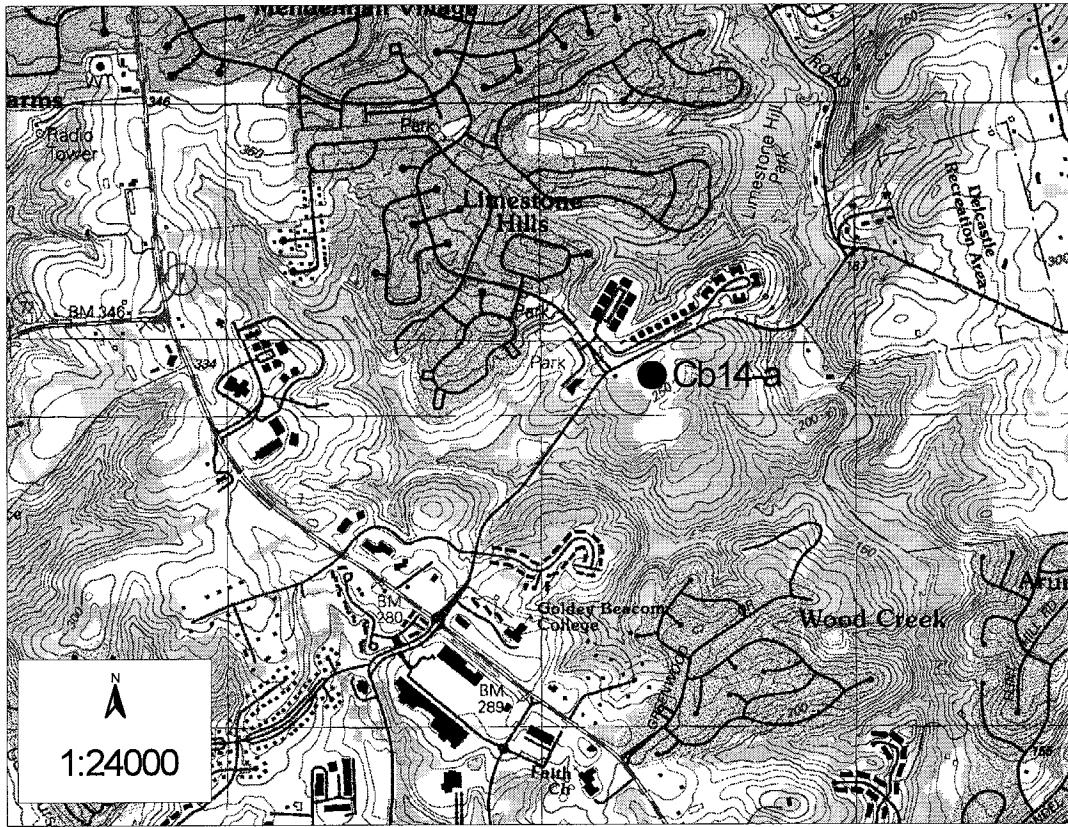
Type section outcrop location map and lithologies for the Bringhurst Gabbro. Map is taken from the U.S. Geological Survey Wilmington North 7.5-minute quadrangle. Many type and reference sections for rock units are on private property. Permission to access these outcrops should always be obtained before visiting.



| DGSID | LAT* | LON* | LITHOLOGY |
|--------|----------|----------|--------------|
| Da15-h | 39 39 15 | 75 45 27 | Gabbronorite |

* Latitudes and longitudes are in NAD27

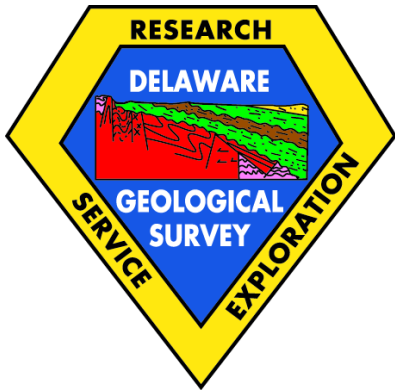
Type section outcrop location map and lithologies for the Iron Hill Gabbro. Map is taken from the U.S. Geological Survey Newark West and Newark East 7.5-minute quadrangles. Many type and reference sections for rock units are on private property. Permission to access these outcrops should always be obtained before visiting.



| DGSID | LAT* | LON* | LITHOLOGY |
|--------|----------|----------|-----------|
| Cb14-a | 39 44 56 | 75 41 05 | Diabase |

* Latitudes and longitudes are in NAD27

Type section outcrop location map and lithologies for the diabase dike. Map is taken from the U.S. Geological Survey Newark East and Kennett Square 7.5-minute quadrangles. Many type and reference sections for rock units are on private property. Permission to access these outcrops should always be obtained before visiting.



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